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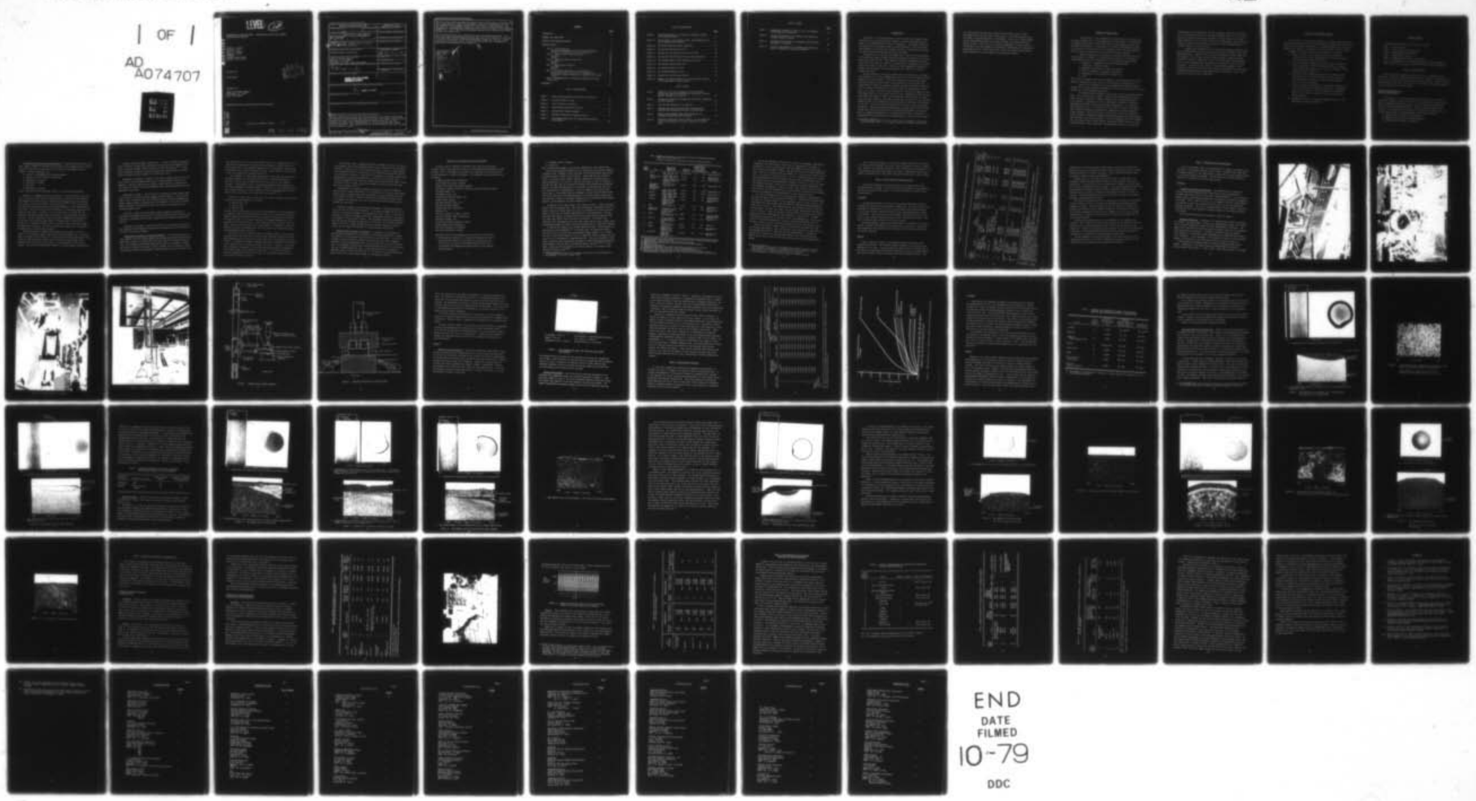

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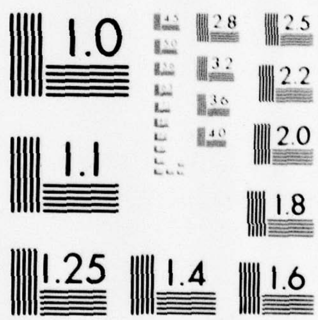

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DEVELOPMENT OF CABLE MATERIAL: IMPROVED WIRE ALLOYS FOR AIRCRAFT ARRESTING DECK PENDANTS

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Fourteen candidate wire alloys were evaluated against the standard deck-pendant wire material, (extra-improved plow steel, EIPS), for their tension, torsion, impact/abrasion resistance, and fatigue-performance properties--as well as their resistance to form brittle transformations at the wire surfaces under impact/abrasion conditions. Cost considerations for the new materials were also included in the evaluation criteria.

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None of the four better-performing candidate alloys showed surface transformations after impact/abrasion, while the EIPS showed a definite transformation to what was concluded to be untempered martensite. The effects of impact/abrasion (and presumably the transformation) caused the EIPS to lose 81 percent of its unabraded fatigue life. All of the better-performing candidate alloys suffered some lesser reduction in fatigue life.

The two candidate alloys that performed the best were MP35N and Elgiloy. However, their rapidly escalating and current high costs are believed to be too high to justify their promise of improved deck-pendant reliability and life. Therefore, the two lower-cost alloys, Inconel 718 and 11R51SH, were recommended for experimental rope manufacture and evaluation.

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INTRODUCTION

The impact of the arresting hook on the wire-rope deck pendant (often referred to as an arresting cable) during an aircraft arrestment produces severe rope deformation at the point of engagement. The damage produced by this high-velocity transverse impact has been observed to include parting and shredding of the rope core, permanent bending or kinking of the strands, and severe interstrand and intrastrand wire notching.

In addition to the initial rope damage due to impact, the deck pendant also experiences severe external abrasion resulting from sliding of the rope across the arresting hook. This sliding is caused by asymmetrical loading of the arresting cable as a result of interactions of longitudinal and transverse stress waves in the cable. Off-center hook engagements increase the abrasive action because of the sliding which must take place to balance dynamic rope loads.

Failure analyses of used deck pendants have revealed that the external rope abrasion is at least as damaging to the rope as is the transverse impact. Sliding of the rope relative to the hook takes place in quick jerks under high rope tension and high contact stress between the rope and the hook. A large amount of energy is required to produce sliding under these conditions and this energy is dissipated in the form of heat at the hook-cable interface. As a result, the wire surfaces adjacent to the hook are heated to very high temperatures in a very short period of time. Immediately after the hook has passed, the large cool mass of the nonabraded rope wires acts to quench the heated wire surfaces. This rapid heating and cooling due to hook abrasion commonly leads to the formation of a brittle layer on the outer wire surfaces of the rope. This layer has been identified in previous work as untempered martensite. Because existing arresting cable is manufactured from AISI 1080 carbon steel wire (an alloy which is particularly susceptible to the formation of untempered martensite), it is highly probable that a martensitic transformation is responsible for the embrittlement. However, work by NAEC*

* Personal communication on July 13, 1976, from L. Moskowitz of the Naval Air Engineering Center to R. Jentgen of Battelle's Columbus Laboratories.

on a deck-pendant failure that occurred on the aircraft carrier "FDR" indicated that the brittle layers were similar to the "white layers" which are formed in bearing materials. Nevertheless, either type of embrittlement results in premature failure by low-cycle fatigue or by high-strain-rate tensile failure. After only a few aircraft engagements, a large portion of the surface of the deck pendant has undergone a transformation. Because the transformed surface is hard and brittle, these outer wires become increasingly susceptible to crack formation and subsequent failure.

SUMMARY AND CONCLUSIONS

The objective of this program was to identify new wire alloys that are more resistant than is extra-improved plow steel (EIPS) to the formation of untempered martensite, or any other brittle transformation product, during impact and abrasion. The formation of a brittle transformation product on the surface of EIPS has lead to the premature failure of deck pendants in the past, with the resultant loss of aircraft and Naval personnel.

Twelve candidate wire materials were selected, and two others were later donated by a vendor, for evaluation with respect to the following characteristics that are of importance in the deck-pendant application:

- Absence of a damaging surface transformation under conditions of impact/abrasion
- Mechanical properties in tension and torsion
- Effect of abrasion on mechanical properties
- Performance in the single-wire fatigue test
- Cost.

EIPS, which is presently used for deck pendants, was evaluated as the control material, bringing the total number of wire materials investigated to 15.

Seven of the candidate wires were eliminated from further testing because their ultimate tensile strengths were below the minimum value of 285 ksi desired for the deck-pendant application.

The remaining seven candidate alloys were tested in an impact/abrasion mode. None of these alloys formed a brittle surface transformation product. EIPS, the control material, however, formed brittle untempered martensite on its surface. The identity of this transformation product was proven by examining the abraded layer before and after subjecting it to a tempering heat treatment in situ. The properties of the wires in tension and torsion after abrasion testing were measured for comparison with their properties before abrasion. Some of the alloys, particularly the Type 302 stainless steels, showed poor abrasion resistance and galling against the hook material and, therefore, they were eliminated. The four candidate alloys that suffered the least loss of metal during abrasion testing were MP35N, Elgiloy, Inconel 718 and 11R51SH. These alloys were evaluated against EIPS in a single-wire

fatigue machine, and EIPS showed the most significant reduction in fatigue life (81 percent) as a result of the impact abrasion test. All of the candidate alloys suffered some lesser reduction in fatigue life; one of them, MP35N, suffered only a 40 percent loss, two of them, Elgiloy and Inconel 818, suffered 52 and 53 percent losses, respectively, and the remaining alloy, 11R51SH, suffered a 75 percent loss.

Taking into consideration all of the service-related properties that were assessed during this study, the two alloys that performed the best were MP35N and Elgiloy. However, their rapidly escalating and current high costs are believed to be too high to justify their promise of improved pendant reliability and life. Therefore, the two lower-cost alloys that performed next best are recommended for experimental rope manufacture and full-scale evaluation. These two alloys, Inconel 718 and 11R51SH, appear to offer improved reliability over that of the currently used EIPS because they suffer no damaging transformations under impact/abrasion conditions. Thus, their service life should be more predictable.

OBJECTIVE AND RESEARCH APPROACH

The objective of this research program is to identify new wire alloys that are more resistant than is extra-improved plow (AISI 1080) steel to the formation during impact and abrasion of untempered martensite or any other products that result in transformations which embrittle the wire surface.

A summary of research tasks for this program is as follows:

(1) Select a series of wire materials which are expected to exhibit good wire-rope manufacturability and good resistance to arresting hook impact and abrasion.

(2) Use a wire abrasion-impact machine previously designed and built by Battelle's Columbus Laboratories (BCL) to conduct wire-abrasion simulations on each wire type selected. (This machine is shown in Figure 1).

(3) Evaluate the wire damage and metallurgical changes created by the abrasion to determine whether the test accurately duplicates that which has been observed during examinations of used deck pendants.

(4) Perform a series of metallurgical and mechanical evaluations of the as-received and abraded wire materials to determine their service potential. Service potential is based primarily on each wire's resistance to failure after severe surface abrasion.

(5) Recommend two (or more) promising candidate alloys for rope manufacture and rope evaluation.

RESEARCH RESULTS

The program was divided into six tasks as follows:

Task 1 - Alloy Selection

Task 2 - Alloy and Wire Characterization

Task 3 - Simulated-Service Evaluation

Task 4 - Metallurgical Analysis

Task 5 - Mechanical Evaluation of Abraded Wire

Task 6 - Recommendation of Promising Candidates for Rope Manufacture

Work on each of these tasks is described in the following paragraphs.

Task 1 - Alloy Selection

Task 1 covers the identification and selection of commercial alloys which, in the form of 0.090-inch-diameter wire, are likely to possess most or all of the characteristics desired in wire for deck pendants. Before covering the selection of the alloys for study on this program, the desired characteristics of such wire will be discussed.

Desired Characteristics of Wire for Deck Pendants

To be viable for use in deck pendants, a wire material not only must possess the properties that ensure that it will perform well in service, but also its properties must be such that it can be stranded, preformed, and closed to form deck-pendant wire rope. Moreover, the wire must be cost effective. Accordingly, this discussion of the desired characteristics of wire for deck pendants is organized under the following headings:

- Characteristics related to serviceability
- Characteristics related to manufacturability
- Characteristics related to economics.

Characteristics Related to Serviceability. A satisfactory arresting cable must possess a number of characteristics because of the complex state of stress which exists within this wire rope as the aircraft hook engages the deck pendant. Primary among these are

- Absence of a damaging surface transformation
- Ultimate tensile strength $\geq$ 285,000 psi
- Resistance to abrasion
- Resistance to impact
- Ductility
- Resistance to fatigue.

These characteristics are discussed briefly in the following paragraphs.

Absence of a Damaging Surface Transormation. Earlier studies by BCL and the U.S. Navy have shown that the heat generated by friction as the aircraft hook engages and slides along the standard deck pendant causes the formation of a brittle layer on the surface of the rope wires.[1,2] This brittle layer was identified as martensite and one possible mechanism for its development is as follows. The rate of heat input by friction is so extremely rapid that the surface of the wire, to a depth of up to several mils, is raised into the austenite temperature range before the heat can be conducted into the body of the wire. (In the high-carbon steels from which standard deck pendants are constructed, the austenite range starts at between about 1350 and 1450 F.) As the heat is conducted into the wire, the surface layer cools very rapidly and martensite is formed. The entire heating and cooling cycle is believed to be completed in much less than 1 second.

The brittle layer in standard deck-pendant steels tends to crack as a result of the bending or impact that occurs during subsequent use. The cracks lead to fracture of the wires in the portion of the strands contacting the hook, either by high-strain-rate tensile failure because of the reduced cross-sectional area of the wire at the crack, or by propagation of the crack by fatigue. Wire fracture necessitates removal of the deck pendant from service.

Ultimate Tensile Strength $\geq$ 285,000 psi. In order to ensure an adequate factor of safety, current deck pendants utilize wires of extra-improved plow steel, having an ultimate tensile strength of about 285,000 psi.[(2)] To preserve the factor of safety, any wire considered for deck-pendant use should have an ultimate tensile strength of at least this value.

Resistance to Abrasion. Because of the severe rubbing action of the aircraft hook on the deck-pendant wire rope, the wire should be resistant to abrasion. The wire should not be subject to metal removal by abrasion and also should not crack or gall when undergoing the high rubbing-contact forces generated by the hook.

Resistance to Impact. The wire rope is subjected to severe impact loading as the aircraft hook initially engages the deck pendant. The rope wires must be able to withstand not only transverse impact, but also longitudinal impact (tensile impact) resulting from the constraint at the ends of the deck pendant provided by the purchase cable, its reeving over sheaves, and the arresting engine itself.

Ductility. Wires in deck pendants require sufficient ductility to withstand the bending that occurs as the aircraft hook contacts the wire rope. Ductility is discussed further under "Characteristics Related to Manufacturability."

Resistance to Fatigue. The cyclic nature of the application of load to deck pendants during landings necessitates consideration of the resistance of the wires to low-cycle fatigue.

<u>Characteristics Related to Manufacturability</u>. To be chosen for use in deck pendants, the wire should possess the aforementioned characteristics and also must be capable of being formed into wire rope of the desired construction. The standard rope-forming operations include (1) stranding, in which the wires are laid around a core to form a strand; and (2) closing, in which the required strands are preformed by bending around a series of rollers and

then laid around a core to form the desired wire rope. Depending on the rope construction, stranding and closing may be performed on either tubular or planetary machines. The standard construction of deck-pendant rope involves six strands, each of which contains 30 wires. These strands are laid around a fiber core during the closing operation.[1]

To be capable of being formed successfully into strand and rope without excessive breakage, the wire material must have a significant degree of ductility and its yield strength must not be too close to its ultimate strength. Unfortunately, there is no general agreement among producers of wire rope regarding the required degree of ductility or the allowable difference (spread) between the yield strength and the ultimate strength that will ensure that quality rope can be made from a given wire.[3-6]

Ductility. Three types of tests have been used to evaluate the ductility of wire for rope applications, as follows:

- Bend or wrap test
- Torsion test
- Tension test.

The bend test, in which the wire is bent around mandrels of varying diameters, is sometimes used in production quality-control work. The smallest diameter mandrel around which the wire can be bent without cracking can be related to the bend ductility of the wire by means of the standard mathematical relationship for outer-fiber strain. Other variations of the bend test are also used. Some are actually wrap tests. Bend ductility is important in that it reflects the type of deformation to which the wire will be subjected during rope manufacturing and in service.

The torsion test, in which one end of a straight length of wire is held stationary while the other end is rotated under controlled conditions around the longitudinal axis of the wire, is also often used for purposes of quality control. The number of complete rotations that can be achieved before failure occurs, and the type of fracture observed, are noted. Actually, the torsion test is much more a measure of the surface quality and internal soundness of a wire sample than it is a measure of ductility.[7] The test is normally applied to different lots of a given alloy for comparison purposes as part of the quality-control function.

On the other hand, a comparison between the number of twists that wire of two different alloys can withstand before fracture occurs has little meaning. Certainly, results in the torsion test should not be used as a major measure of the expected ability of a new alloy to be formed into strand and rope and to perform well in service. While wire is subjected to torsional loads during stranding and closing and during service, the wire is not called upon to suffer the number of twists per unit length that it must bear in order to pass the quality-control tests. Some wires having low torsion values have been made into excellent rope.[4]

Measurements of elongation during a tension test are not considered viable quality-control indications of the suitability of wire for rope making. Quality rope is commonly made from wire having a tensile elongation of only 1-1/2 percent, or less. Values of reduction in area during a tension test are thought to be important, but are not generally used for quality-control purposes in rope mills.

Difference Between Yield and Ultimate Strengths. During rope manufacture, the wire is plastically deformed. If the yield strength of the wire is close to its ultimate strength, two problems may arise. First, it may not be possible to control the tension during the rope-making processes as precisely as necessary to avoid tensile breaks. Wire breakage increases the manufacturing cost and may even make it impossible to form rope in the desired lengths. Second, in service, sudden breakage may occur without warning; obviously, sudden failure cannot be tolerated in the deck-pendant application.

<u>Characteristics Related to Economics</u>. In addition to possessing the characteristics necessary for serviceability and manufacturability, a viable wire material for deck-pendant rope must also be cost effective. Cost effectiveness in this application relates the total life-cycle costs (original purchase price plus maintenance cost) to the service life for each wire material. The original purchase price incorporates both the price of the wire and the cost of manufacturing the rope. A deck pendant made of a relatively expensive alloy could be cost effective if its service life were sufficiently greater than that of deck pendants made of less-expensive alloys.

Selection of Candidate Wires for Evaluation

To ensure that no worthwhile candidate alloy wire was overlooked, personal contacts were made with major U.S. and Canadian manufacturers of high-strength wires to determine the availability, properties, and selling prices of such materials at 0.090-inch diameter. The companies surveyed included the following:

Allegheny Ludlum Steel Corporation
AL Tech Specialty Steel Company
Branford Wire and Manufacturing Company
The Elgiloy Company, Division of American Gage and Machine Company
Greening Donald, Ltd.
Huntington Alloys, Inc.
International Nickel Company, Inc.
Latrobe Steel Company
Maryland Specialty Wire, Inc.
National Standard Company
Paulsen Wire Rope Corporation
Sandvik, Inc.
The Steel Company of Canada, Limited
Stellite Division, Cabot Corporation
Techalloy Company, Inc.
Titan Steel and Wire Company, Limited
United States Steel Corporation
Wire Rope Corporation of America
Wire Rope Industries, Limited.

The alloy wires for investigation were selected on the basis of:

- Metallurgical structure as a function of temperature; hence, the anticipated effect on the structure and properties of the wire as a result of the surface heating that occurs as the aircraft hook engages and slides along the deck pendant during landing.

- Ultimate tensile strength.
- Ductility.

These criteria were judged to be the most important for this application.

The 12 most promising commercial-alloy candidates (Wire Material Numbers 1 through 3 and 5 through 13) were selected for the deck-pendant application by Battelle based on these three criteria. These materials are listed in Table 1, along with their nominal chemical composition, selling prices*, tensile properties, and vendors. The last two alloys in Table 1, Pyromet 31 and Type 316 HSM, were not selected by Battelle for purchase and evaluation. Rather, they were provided gratis by the vendor as new materials that they felt were worthy of investigation. As will be shown in the section that covers Task 2, the ultimate tensile strengths of wires for both these alloys were much lower than the minimum required for the deck-pendant application. Also included in Table 1 is similar information for the standard deck-pendant material, extra-improved plow steel (Material No. 4).

In addition to the aged Elgiloy wire listed in Table 1, drawn-to-tensile Elgiloy wire was ordered also. The vendor anticipated that Elgiloy wire cold drawn to about 54 percent reduction in area, following the previous process anneal, could meet the tensile requirements for this application. However, the vendor was unable to provide BCL with any drawn-to-tensile Elgiloy wire that they (the vendor) felt was worthy of evluation. The vendor later indicated that the preparation of such wire would require time to modify their processing procedures to obtain the desired properties at 0.090-inch diameter.

In earlier BCL research, two alloys, MP35N and DA921, showed promise for application in deck pendants.[(2)] The former alloy is included in Table 1. The latter alloy, obtained from International Nickel Company, Inc., (INCO) for use in the earlier research, is not a commercial alloy at present and currently is not a candidate for commercialization. This was confirmed in telephone discussions with appropriate personnel at INCO locations in Huntington, West Virginia, New York City, and Sterling Forest, New York.[(8-10)] Alloy NS355, which also was evaluated in the earlier study, is no longer a commercially available item.[(11)]

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* Selling prices are given for the period just prior to the initiation of the program as well as of June, 1979.

TABLE 1. COMMERCIAL ALLOY WIRE CANDIDATES FOR DECK-PENDANT APPLICATION, BASED ON METALLURGICAL STRUCTURE, ULTIMATE TENSILE STRENGTH AND DUCTILITY

The Standard Deck-Pendant Material, Extra-Improved Plow Steel, is included for Comparison

Wire Material Numbers	Alloy	Nominal Chemical Composition[1], weight percent	Metallurgical Condition	Selling Price of 0.090-Inch Diameter Wire[2], dollars per pound		Vendor
				July, 1976	June, 1979	
1	NS 18-2	18Cr, 12MN, 1.6Ni, 0.34N, 0.5Si, 0.1C, bal Fe	Stress relieved	2.14	1.92	National Standard Co.
2	Type 302 Special Process[3]	0.15maxC, 2maxMu, 1maxSi, 17/19Cr, 8/10Ni, bal Fe	As drawn	N/A	2.20	Branford Wire and Manufacturing Co.
3	17-7 PH	0.09maxC, 1.0maxMn, 0.04max P, 0.03maxS, 1.0maxSi, 16/18Cr, 6.5/7.75Ni, 0.75/1.5Al, bal Fe	CH-900[4]	2.99	2.96	National Standard Co.
4	Extra-Improved Plow Steel (Standard Deck-Pendant Material)	0.8C, 0.5Mn, 0.04maxP, 0.05maxS, bal Fe	As drawn	~0.31	0.44[5]	Greening Donald, Ltd.
5	Type 302[6]	17/19Cr, 8/10Ni, 2maxMn, 1maxSi, 0.11C, bal Fe	As drawn	N/A	1.38[5]	Greening Donald, Ltd.
6	Type 304	18/20Cr, 8/12Ni, 2maxMn, 1maxSi, 0.08maxC, bal Fe	As drawn	1.62	~1.44[5]	Greening Donald, Ltd.
7	UCAR 302[7]	0.15maxC, 2maxMn, 1maxSi, 17/19Cr, 8/10Ni, bal Fe	As drawn	N/A	2.30	Union Carbide Corp., Linde Division[8]
8	18-18 Plus	0.15maxC, 17/19Cr, 17/19Mn, 0.75/1.25Mo, 0.75/1.25Cu, 0.4/0.6N, 1.0maxSi, 0.04maxP, 0.04maxS, bal Fe	As drawn	N/A	2.60	Maryland Specialty Wire, Inc.
9	MP35N	35Ni, 35Co, 20Cr, 10Mo	As drawn	15.56	50.00	Maryland Specialty Wire, Inc.
10	ALMAR 18 (300) Maraging Steel	18/19Ni, 8/9.5Co, 4.6/5.2 Mo, 0.5/0.8Ti, 0.05/0.15 Al, Si+Mn <0.2max to 0.3maxC, bal Fe	Aged	4.78	9.27	AL Tech Specialty Steel Co.
11	Elgiloy	40Co, 20Cr, 15Ni, 7Mo, 2Mn, 0.04Be, 0.15C, 16Fe	Aged[9]	17.62	44.79	The Elgiloy Company, Division of American Gage & Mach. Co.
12	Inconel 718	19Cr, 18.5Fe,0.9Ti0.5 Al,3.05Mo,5.3Cb,Ta, 0.3 Si,0.2Mn,0.04C,0.005 B, bal Ni	Aged[10]	7.99	10.89	Techalloy Co., Inc.
13	11R51SH	0.09C-1.2Si-1.3Mn-17 Cr-8Ni-0.7Mo bal Fe	As drawn	2.40	3.10	Sandvik, Inc.
14	Pyromet 31	55.27Ni,22.59Cr 2.02Mo,2.32Ti,1.35Al, 0.85Cb+Ta,0.12Si, 0.10Mn,0.04C,0.005P	As drawn	N/A	16.00	Maryland Specialty Wire, Inc.
15	Type 316 HSM	17.40Cr,10.44Ni, 2.35Mo,1.66Mn, 0.53Si,0.07C, 0.020P,0.003S, bal Fe	As drawn	N/A	2.50	Maryland Specialty Wire, Inc.

(1) For the following alloys, the chemical composition is the heat analysis furnished by the vendor, rather than a nominal chemical composition: Pyromet 31, Type 316 HSM.
(2) Quotations for 3000- to 5000-lb quantities. Prices do not include heat treatment.
(3) Manufactured using an undisclosed "special process" which does not involve cryogenic deformation.
(4) Aged one hour at 900 F.
(5) Price does not include import duty.
(6) Relatively high carbon content (e.g., 0.11 weight percent) within the specification range for Type 302.
(7) Cryogenically deformed Type 302 stainless steel. Alloy is now known as Cryotec 302.
(8) Now marketed by AL Tech Specialty Steel Company, under license from Union Carbide Corporation.
(9) Wire cold drawn to about a 45-48 percent reduction in area, then aged at BCL at 900 F for 5 hours, air cooled.
(10) As-drawn (spring temper) wire double aged at BCL as follows: 1325 F, 8 hours, air cooled; 1150 F, 8 hours, air cooled. Both aging treatments were carried out in air.

Two of the candidate alloys listed in Table 1 may undergo a martensitic transformation* when rapidly cooled from the temperatures that might be achieved as a result of abrasion of the deck pendant by the aircraft hook. In one of the alloys [ALMAR 18 (300)], the martensite is a low-carbon martensite that should not be significantly detrimental if it forms on the surface of the wire. In order for the second alloy, 17-7 PH, to form martensite on cooling, the time-temperature profile through which the wire is heated must induce sufficient diffusion and metallurgical changes to result in a matrix in which the chromium and carbon levels are low enough that the M_s** temperature is above ambient temperature. However, the very short time for which the wires are heated in the deck pendant may well prevent this occurrence and, therefore, prevent the formation of fresh martensite in this particular alloy.

All of the candidate alloys were expected to undergo a slight degree of surface softening as they are heated by abrasion. The degree of softening and the depth of softening depend on the temperature profile across the wire, the time duration of the heating, and the chemical composition and metallurgical structure of the wire. The temperature and time parameters depend on the rate of heat input, the total heat input, and the thermal conductivity and emissivity of the wire. Thus, the specific conditions of the abrasion are of fundamental importance, although they are difficult to characterize. A slight softening of the surface of the wire is much less damaging than is the formation of a high-carbon martensite; in fact, surface softening may even be helpful in that it allows localized yielding in areas of high surface stress.

Most of the alloys listed in Table 1 already have been made into rope for various applications. Thus, the ability of the majority of these wires to be stranded and closed to form rope has been demonstrated. As examples, Elgiloy rope is used in a control-cable system in the YF12A aircraft and MP35N rope is used in sour oil wells and as armor wire for electromechanical cables.

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* Extra-improved plow steel, the standard deck-pendant material, obviously also undergoes a martensitic transformation but this material is considered only as a "control" material for this program.

** The temperature at which martensite begins to form on cooling.

As is obvious from Table 1, all of the candidate alloys are more expensive than is extra-improved plow steel; some are extremely costly by comparison. However, one important objective of the research was to determine if any of these more expensive alloys might show property improvements that imply a greatly increased service life and/or decreased likelihood of sudden failure.

Task 2 - Alloy and Wire Characterization

The initial candidate wire-rope materials were characterized before simulated-service testing. The characterization determined the acceptability of the wire materials with respect to specified mechanical properties and microstructure.

Procedure

The characterization of the alloy wires involved mechanical testing (tension and torsion) and metallographic examination. The tensile tests were performed in triplicate for wires of a 10-inch gage length (maintaining an 11 to 12-inch distance between the gaps) using a Baldwin-Universal tensile test machine. The torsion tests were performed in quintuplicate for wires with a 7-inch distance between the grips using a Carlson Twist Tester. Both tests proceeded until failure of the wires occurred.

The metallographic examination was performed to characterize the surface quality, internal cleanliness, and microstructure of the wires. Transverse and longitudinal wire specimens were inspected in both the as-polished and the etched conditions.

Results

Table 2 shows the results of the mechanical-characterization tests (tension and torsion). The condition (heat treatment) of the wires is also indicated in the table. The seven materials listed below the dashed line in the table were eliminated from further consideration once it was established that one or several of their properties were below acceptable limits. The

TABLE 2. MECHANICAL PROPERTIES OF COMMERCIAL-ALLOY-WIRE CANDIDATES FOR DECK PENDANTS

Wire Material Number	Alloy	Heat Treatment	Reduction in Area, Percent	Elongation, Percent in 10 Inches	Yield Strength,(1) psi	Ultimate Tensile Strength, psi	Number of Turns to Failure in Torsion
13	11R51SH	As drawn	40.5	<0.5	287,500	340,000	7.8
7	UCAR 302(2)	As drawn	44.6	<0.5	310,000	318,800	2.4
10	ALMAR 18 (300) Maraging Steel	Aged	46.2	<0.5	310,200	316,400	2.1
11	Elgiloy	Aged 900 F,5 hr, air cooled	33.2	<0.5	277,000	313,000	1.8
12	Inconel 718	Double age: 1325 F, 8 hr, air cooled; 1150 F, 8 hr, air cooled	7.0	0.5	283,000	293,000	3.3
4	Extra-Improved Plow Steel	As drawn	46.7	1.5	237,900	288,100	25.2
9	MP35N	As drawn	47.0	2.0	224,100	286,200	3.5
2	Type 302 Special Process (3)	As drawn	44.8	<0.5	260,500	278,500	17.4
8R(5)	18-18 Plus	As drawn	2.9	<0.5	231,000	284,000	4.2
5	Type 302(4)	As drawn	46.6	<0.5	231,300	270,600	4.8
1	NS 18-2	Stress relieved	42.4	1.4	233,200	270,300	3.0
6R(5)	Type 304	As drawn	45.8	(6)	231,900	261,200	5.2
14	Pyromet 31(7)	As drawn	6.2	0.5	217,000	258,000	3.4
15	Type 316 HSM	As drawn	41.3	2.2	202,000	241,000	2.4
3	17-7PH	CH-900(8)	43.7	<0.5	222,700	238,000	10.4

(1) Yield strength at 0.2 percent offset.
(2) Cryogenically deformed Type 302 stainless steel.
(3) Manufactured using an undisclosed "special process" that does not involve cryogenic deformation
(4) High-carbon (0,11 weight percent) Type 302.
(5) Replacement wire, provided by manufacturer as a substitute for earlier wire of this material which had 0 percent reduction in area in tensile tests at Battelle.
(6) Values varied from <0.5 to 1.0 percent.
(7) The failures of this alloy in tension occurred at the edge of the grips.
(8) Aged 1 hour at 900 F.

elimination of the seven materials from further testing was discussed and agreed upon during a meeting held between Battelle researchers and the NAVAIR Technical Monitor, Mr. Michael Valentine. Thus, eight wire materials were accepted for further testing and examination.

Tensile tests for the lower six alloys in Table 2 caused them to be eliminated because of unacceptable ultimate tensile strengths (less than 285,000 psi). The 18-18 Plus alloy was rejected for having a very low reduction in area and marginal tensile strength. The type 302 Special Process Alloy was retained (even though it had a slightly substandard ultimate-tensile-strength value), because it exhibited a high number of turns to failure in torsion. Its turns-to-failure value was second only to that of the control material, extra-improved plow steel.

For the wires accepted for further testing (the top eight wire materials listed in Table 2) optical microscopy was performed on metallographically prepared specimens. The wire surface quality was normal for commercially produced wire products and was deemed acceptable. The internal cleanliness of the wires examined was typical for the respective alloys, and no unusual concentration of unusually large nonmetallic inclusions was present in the wire sections studied.

The observed microstructures of the specimens of the candidate wire materials were typical of the structures expected for each material (for the specific type of processing and/or aging to which each material had been subjected). Moreover, the structures were similar to the internal (unaffected) structures of the metallographic sections that were prepared subsequently through the cross-sections of abrasion-impact tested wires.

Further comments on the microstructures of the wire materials will be reserved for the text of the Task 4 metallurgical analysis section of this report where these structures are presented and described.

Task 3 - Simulated Service Evaluations

One of the primary tasks in this program was to submit the selected wire materials to high-speed, abrasive contact using a simulated hook under load in a manner similar to that experienced by rope wires in a deck pendant during an off-center aircraft arrestment. The work done in accordance with that objective is described in the following sections.

Procedure

Abrasion-Test Machine Procurement. The machine used to produce the desired high-speed abrasive-contact conditions was built by Battelle's Columbus Laboratories (BCL) in an earlier related program[(2)]. At the time the program began, this abrasion machine was in storage at the Naval Air Engineering Center. After a period of time, it was shipped to BCL and, unfortunately, was received in such poor condition that it could not be used without substantial renovation. All of the corroded hydraulic lines (Figure 2) had to be replaced and the pitted hydraulic cylinders (Figure 3) were either replaced or restored.

The refurbished abrasion-test machine is shown in Figure 4.

Operating Procedures. In general, the abrasion-test machine is operated as follows: The drop weight is raised to a predetermined height, and a safety bar is inserted beneath the weight as shown schematically in Figure 5. The wedge cam is positioned so that the desired horizontal travel of the simulated hook surface will be achieved. A hydraulic cylinder raises the pressure plate assembly to allow the follower mechanism and the simulated hook surface to be retracted. A wire specimen is then inserted in a groove in the specimen support and connected to the tensioning cylinder as shown in Figure 6.

Upon release, the dropped weight accelerates downward gaining kinetic energy. Subsequently, the weight strikes the wedge-shaped cam which is driven downward after impact. A cam follower rides along one side of the wedge

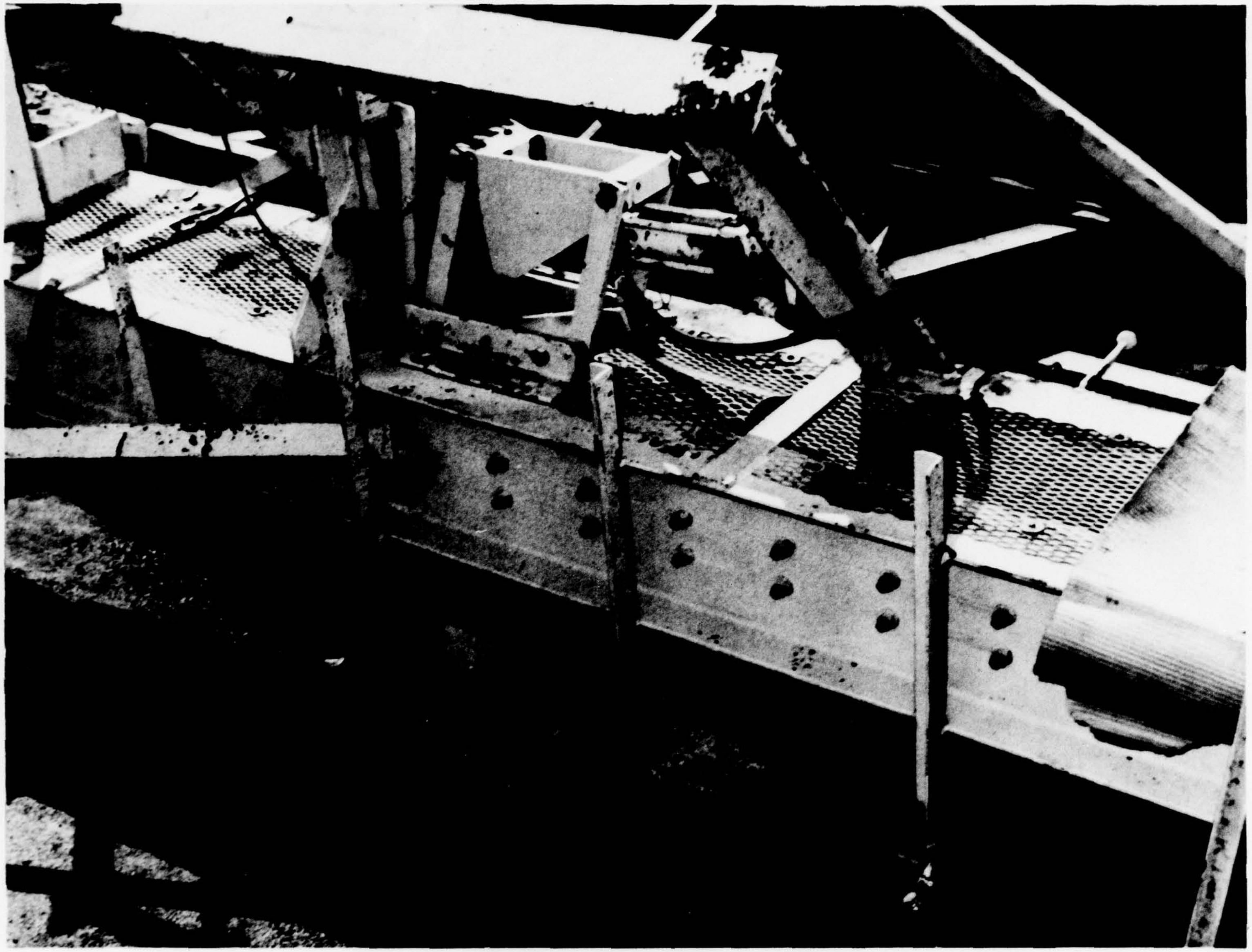


FIGURE 1. ABRASION TEST MACHINE AS-RECEIVED AT BATTELLE

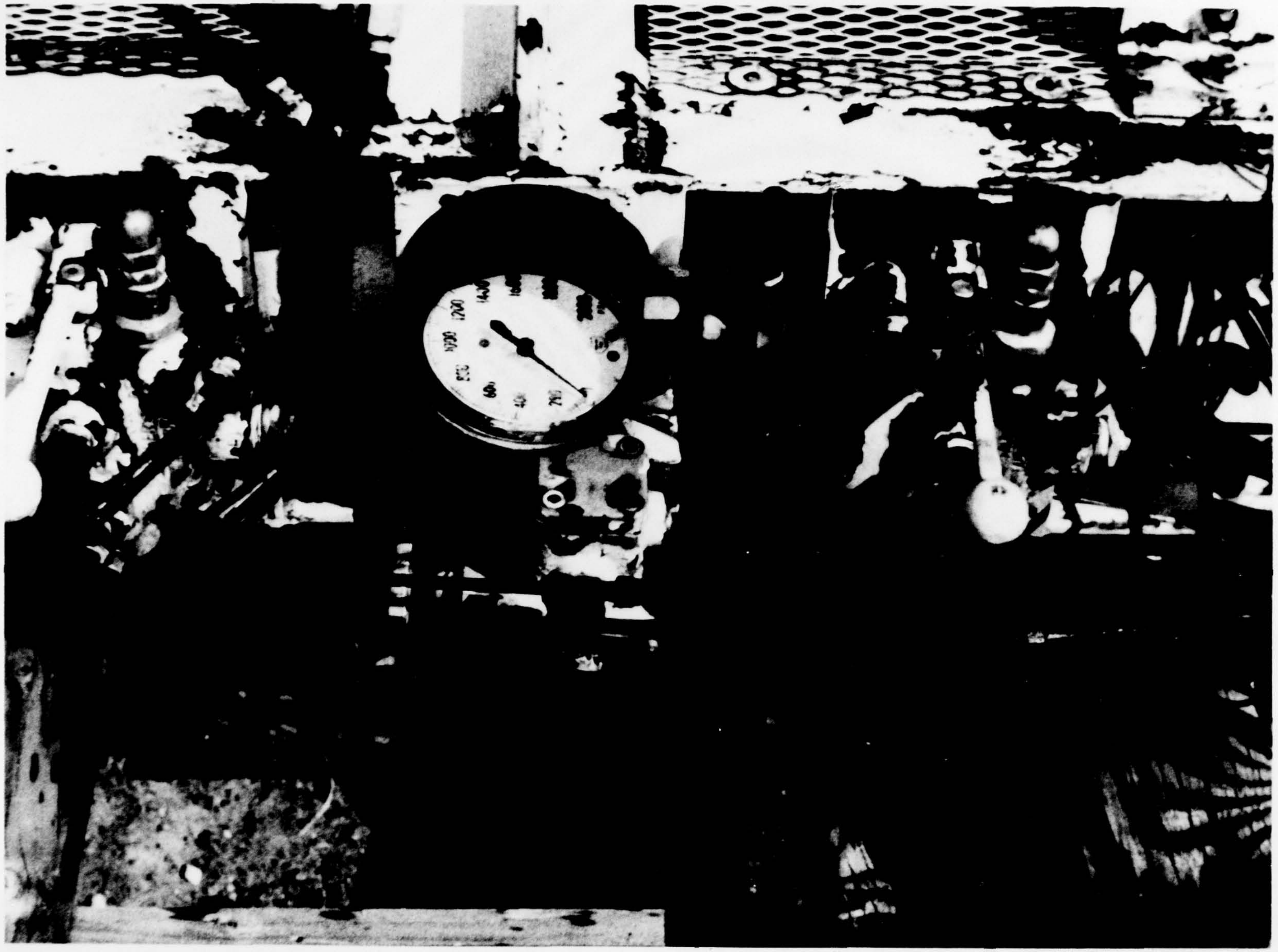


FIGURE 2. CORRODED HYDRAULIC LINES

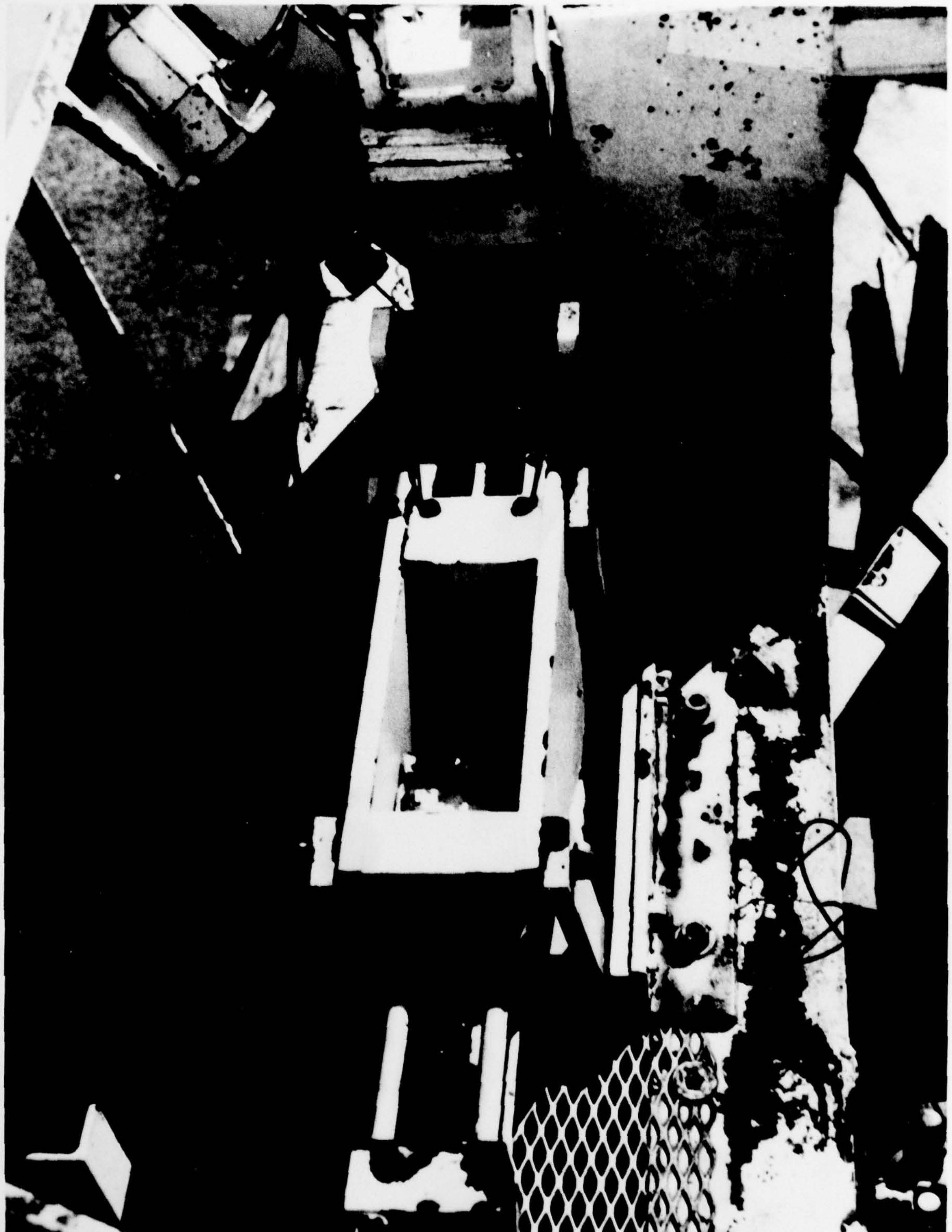


FIGURE 3. CORRODED HYDRAULIC CYLINDERS

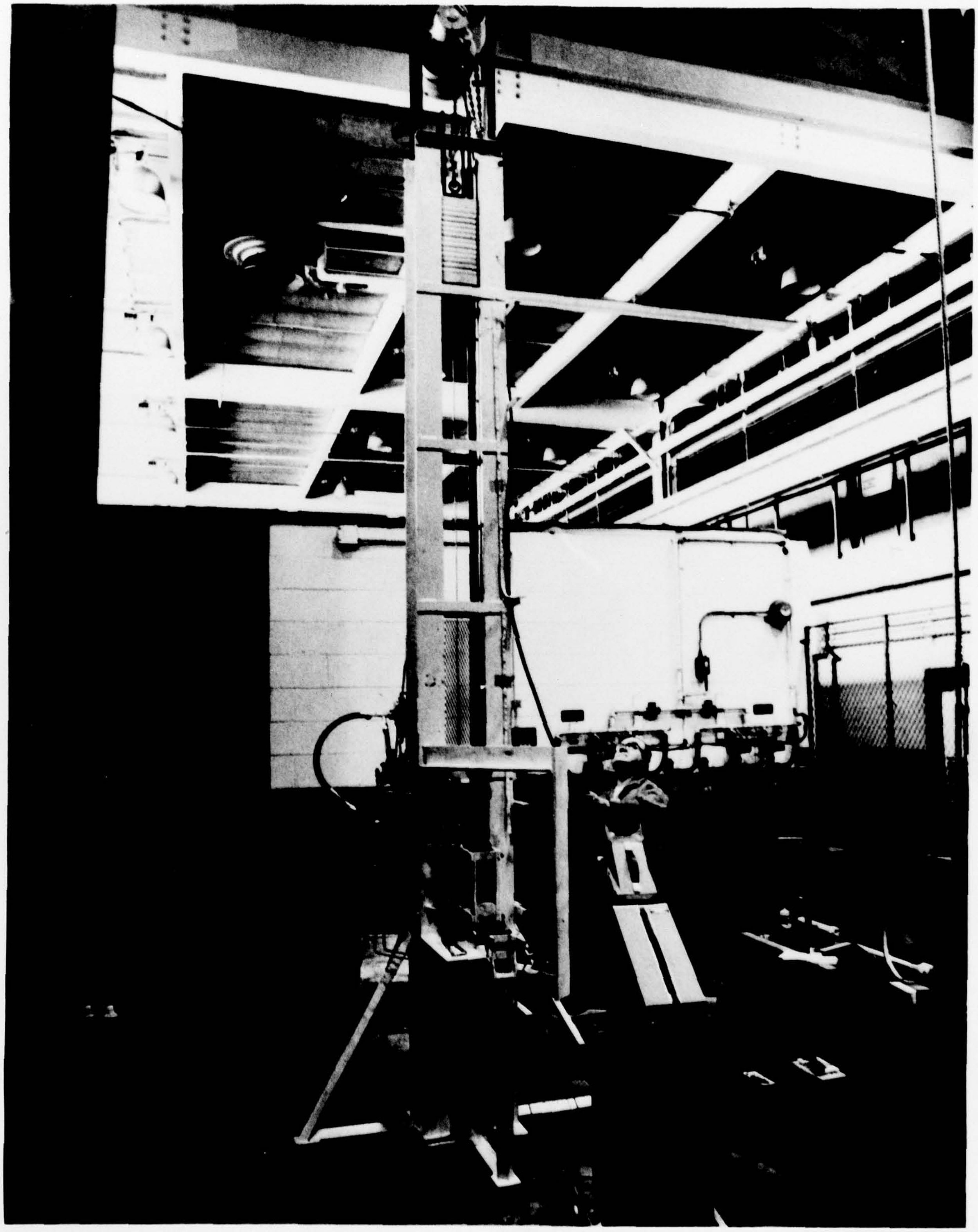


FIGURE 4. REFURBISHED ABRASION-TEST MACHINE

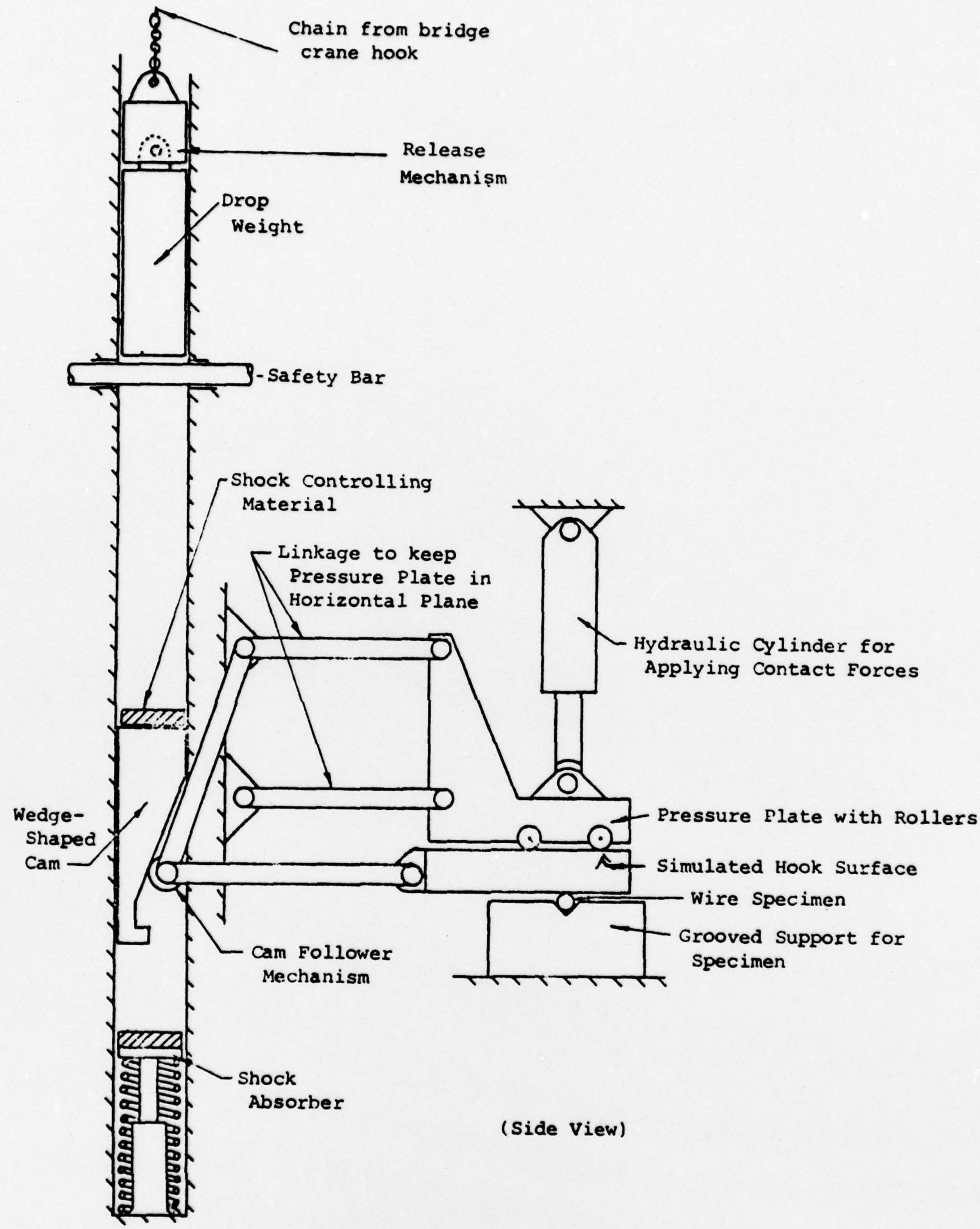


FIGURE 5. ABRASION TEST MACHINE SCHEMATIC

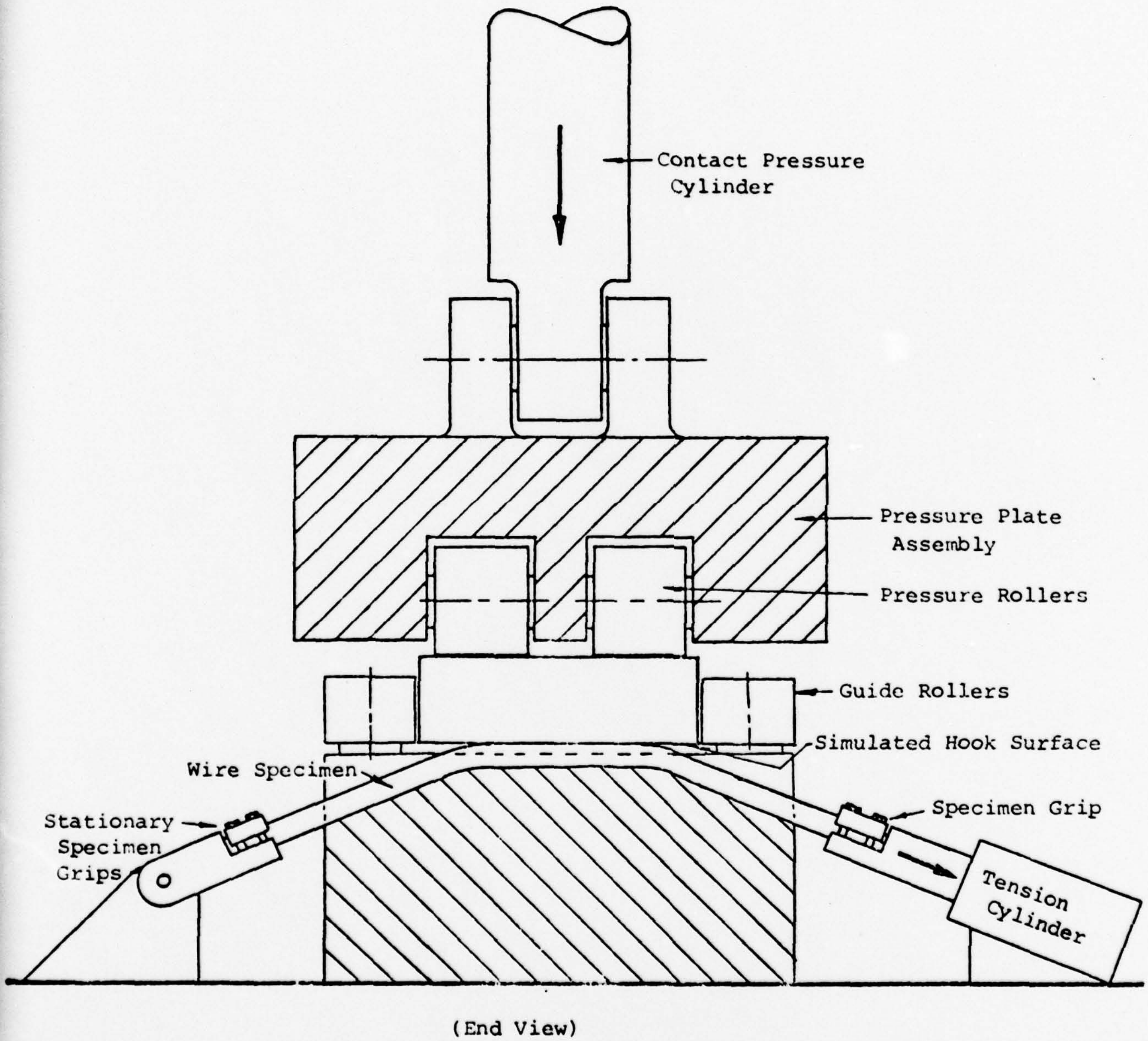


FIGURE 6. SPECIMEN TENSIONING AND SUPPORT SYSTEM

while the other side of the wedge is supported by a lubricated bearing surface. The follower is restrained vertically by a linkage arrangement and is connected to the simulated hook surface so that only horizontal forces are applied. The simulated hook surface is driven forward under pressure until the follower reaches the end of the tapered portion of the wedge. The total travel of the simulated hook surface is determined by the initial position of the wedge and cam-follower mechanism.

The overall height of the machine is fifteen feet. The drop weight is raised to the desired height with an electric hoist mounted on a framework atop the machine. Hydraulic power is supplied to the machine from a portable power supply.

The hook itself is made of 17-4 PH and is coated with Metco 16C according to Naval Air Engineering Center Material and Process Requirement 1031[12]. It is cleaned (by hand with a carborundum stone) of any wire material debris before each series of tests for a given alloy. Before each wire sample is abraded, the simulated hook and test wire are cleaned with kerosene and trichloroethylene.

Results

Hook-Velocity Measurements. The general performance capabilities of the abrasion test machine were demonstrated in an earlier program at Battelle[2]. The actual hook velocities attained in the current study (after refurbishment of the machine) were checked carefully before abrasion testing and at intervals during the testing of each alloy examined. Essentially constant hook velocities were noted throughout the program. Figure 7 illustrates a typical displacement-versus-time (velocity) trace for the simulated hook. This trace was developed using a storage oscilloscope to capture the output of a linear potentiometer attached to the hook.

38 msec.

4.0 in.

Y ↑

X →

Drop Weight = 100 in.
Weight = 332 lbs
Compressive Force = 7500 lb

Wire Material - Extra-Improved Plow Steel
Wire Tension - 1000 lbs
Average Velocity - 8.8 ft/sec.

FIGURE 7. DISPLACEMENT-TIME TRACE FOR SIMULATED HOOK DURING WIRE ABRASION

The average velocity recorded for the simulated hook during all testing was 8.8 ft./sec., with variations in velocity from the average that were no greater than 0.4 ft./sec.; therefore, the observed values for hook velocity were obviously affected by friction between the falling weight and the track and friction between the hook and the test specimen.

Abrasion Measurements. All of the wires tested were subjected to two simulated hook engagements under the conditions specified in Figure 7. One dozen wire samples of each of the seven remaining candidate alloys were tested. The samples were numbered in the same sequence that they were tested. The primary experimental measurement coming directly from the abrasion tests was

reduction in diameter as shown in Table 3. Typically, the diameter reduction (flattening) observed represented a combination of material lost by transfer to the hook and material that was displaced and yet remained adherent to the wire. These two types of material loss were not differentiated directly, although it became quite apparent that those candidate alloys most suspectible to material loss by transfer showed increasingly severe overall material removal as successive wires were tested.

The data for diameter reduction after two hits, given in Table 3, is plotted in Figure 8 for the various wire alloys tested. In all cases, the amount of material removed from the wire samples increased as more debris from the alloy being tested built up on the simulated hook. The extent to which material build-up on the hook increased the removal of wire material in later tests was greatest for the two types of 302 stainless steel wires. After twelve wire tests, there was no indication of stabilization of material removal; apparently, the galling effect of the 302 stainless-steel materials sliding against themselves (produced by a transfer film) is quite severe. An intermediate level of material removal during abrasion was noted for three other wire materials - 11R51SH, Maraging steel, and extra-improved plow steel. The least material removal was observed in the remaining three alloys - Inconel 718, MP35N, and Elgiloy. These results provided some definite indications of the abrasion resistance of these various materials under high-speed sliding conditions such as those characteristic of deck pendant-hook contacts.

Task 4 - Metallurgical Analysis

In this task, abraded-wire samples were examined metallurgically to evaluate the extent of damage in the material under the abraded surface. If a phase transformation in the material beneath the abraded region resulted in the formation of a hard, brittle microconstituent, the alloy would then be eliminated from further consideration. This task resulted in identifying those materials that did or did not form hard, brittle areas and, therefore, helped to establish another criterion for use in the selection of acceptable wire-rope alloys for deck pendants.

TABLE 3. WIRE MATERIAL REMOVED DUE TO ABRASION

Sample Number	Control Alloy Extra-Improved Plow Steel (EIPS)	Candidate Alloys Reduction in Diameter, in.[a]						
		11R51SH	MP35N	ALMAR 18 (300) Maraging Steel	UCAR 302 Stainless Steel	Elgiloy	302 Stainless Steel Special Process	Inconel 718
1	0.0030[b]	0.0010	0.0005	0.0020	0.0020	0.0000	0.0030	0.0000
2	0.0030	0.0010	0.0000	0.0020	0.0030	0.0010	0.0050	0.0010
3	0.0030	0.0020	0.0005	0.0030	0.0030	0.0010	0.0060	0.0010
4	0.0040	0.0020	0.0015	0.0035	0.0030	0.0010	0.0070	0.0010
5	0.0030	0.0030	0.0010	0.0030	0.0030	0.0010	0.0070	0.0010
6	0.0040	0.0030	0.0015	0.0030	0.0040	0.0010	0.0080	0.0010
7	0.0040	0.0030	0.0010	0.0040	0.0040	0.0010	0.0090	0.0010
8	0.0040	0.0040	0.0015	0.0050	0.0050	0.0020	0.0100	0.0010
9	0.0050	0.0070	0.0015	0.0040	0.0060	0.0020	0.0110	0.0010
10	0.0050	0.0030	0.0010	0.0040	0.0070	0.0020	0.0110	0.0010
11	0.0050	0.0040	0.0015	0.0040	0.0080	0.0020	0.0120	0.0010
12	0.0050	0.0040	0.0015	0.0040	0.0090	0.0010	0.0130	0.0010
Nominal Diameter of Original Wire	0.0890	0.0900	0.0895	0.0890	0.0900	0.0900	0.0910	0.0900

(a) After two hits in the Battelle Impact-Abrasion Machine under conditions listed in Figure 7.
(b) Accuracy to within ± 0.0005 inch.

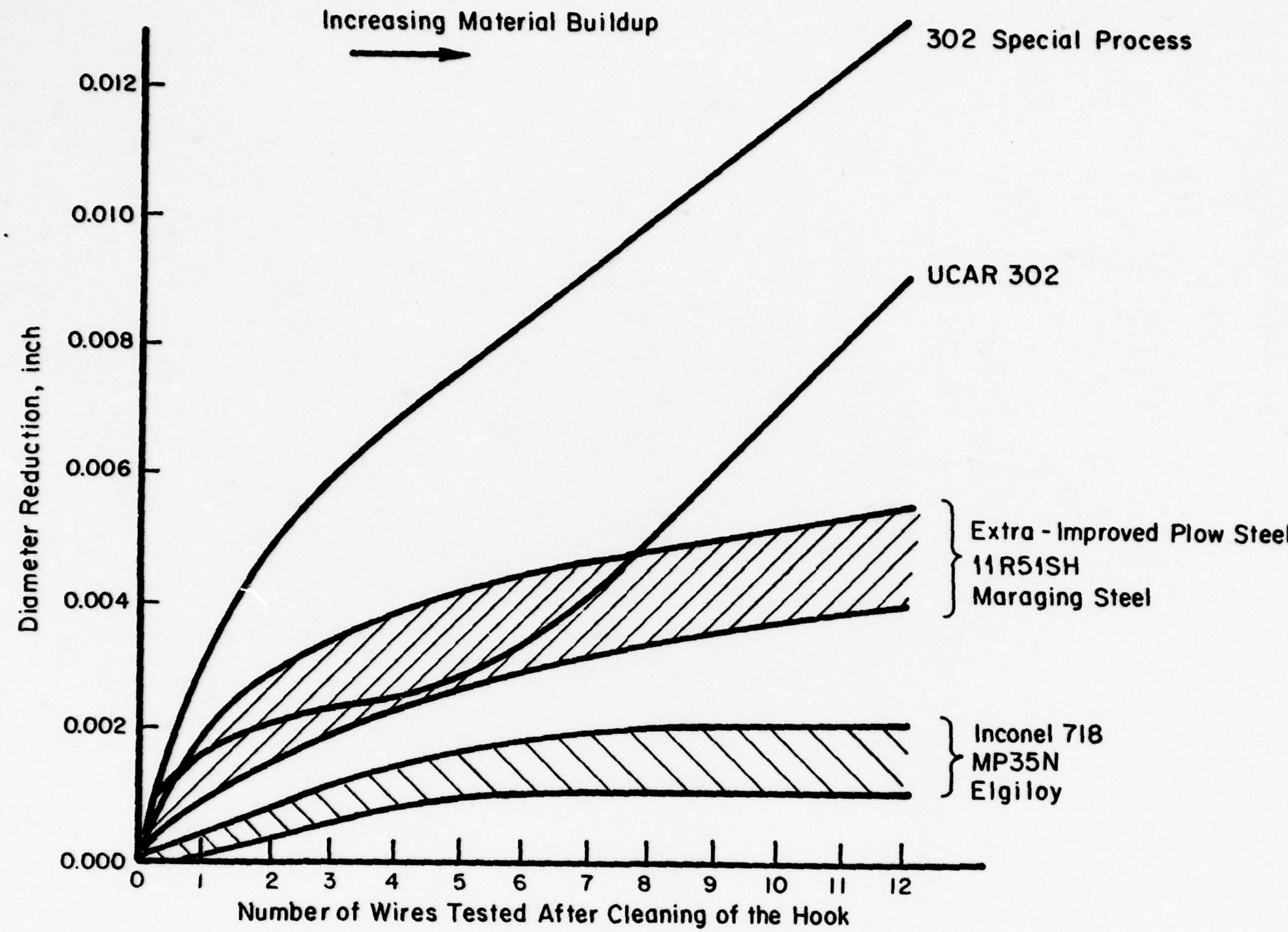


FIGURE 8. ABRASION RESISTANCE AS A FUNCTION OF MATERIAL BUILDUP ON THE SIMULATED HOOK

Procedure

Longitudinal and transverse specimens of abraded wire were prepared metallographically for low- and high-magnification examination. Various etchants were used to delineate the grain structures in the different alloys, as indicated beneath the photomicrographs presented later in describing results of this task. Knoop-microhardness measurements were taken in the abrasion-affected zones of the wires and, also, completely across each longitudinal and transverse wire cross section. The depths of the affected zones in the wire materials (beneath the abraded surface) caused by the abrasion were measured with a precision electronic digital-micrometer stage in conjunction with a light microscope. Photomicrographs were made, as needed, to illustrate the various conditions encountered.

An experiment was performed to verify that the white-etching layer at the surface of the abraded region of the extra-improved-plow-steel wire was untempered (white) martensite. A small sample of the abraded wire was heated for 1 hour in a small electric furnace operating at 600 F. The specimen was then water quenched and prepared metallographically for examination with the microscope.

Results

Samples of the eight accepted candidate wire-rope materials were examined metallographically to ascertain the type and extent of physical and microstructural damage sustained by the wires as a result of impact-abrasion testing. Some type of affected zone existed beneath the abraded regions in all of the candidate wires. However, the white-etching martensite phase was present beneath the abraded region of only the extra-improved-plow steel (EIPS) wire and the ALMAR 18 Maraging-steel wire. This finding and the results of microhardness measurements shown in Table 4 revealed that only the EIPS wire formed a hard, brittle phase as the result of abrasion. The measurements of the depths of the affected zones beneath the abraded-surface regions also are shown in Table 4. Note that the alloys Inconel 718, MP35N and Elgiloy had

TABLE 4. HARDNESS AND AFFECTED-ZONE DEPTHS (FROM ABRASION) OBTAINED FROM TRANSVERSE SECTIONS OF ABRADED WIRES

Alloy	Wire Material Number	Depth of Affected Zone From Abrasion, inch	Average Knoop-Hardness of Material Under the Abraded Surface	Unaffected Wire Matrix
11R51SH	13	0.0047	392 (39)[(a)]	651 (56)[(a)]
UCAR 302	7	0.0078	371 (37)	639 (55)
ALMAR 18 (300) Maraging steel	10	0.0068	385 (38)	640 (55)
Elgiloy	11	0.0009-0.001	397 (40)	640 (55)
Inconel 718	12	0.0008	448 (43)	580 (52)
MP35N	9	0.0009	360 (36)	522 (49)
Extra-improved plow steel	4	0.0060	895 (67)	537 (50)
Type 302 Special Process	2	0.0090	355 (35)	532 (49)

(a) The numbers in parentheses are Rockwell C values obtained by conversion of the Knoop-hardness numbers.

the thinnest affected zones (Inconel 718 had the thinnest zone), and the Type 302 stainless steels had the deepest affected zones.

Also, significant softening occurred in the affected zones of each of the wires, except for the EIPS. Examination of the respective microstructures at high magnification allowed explanations to be advanced to account for the softening phenomenon for each alloy. These explanations will be presented later.

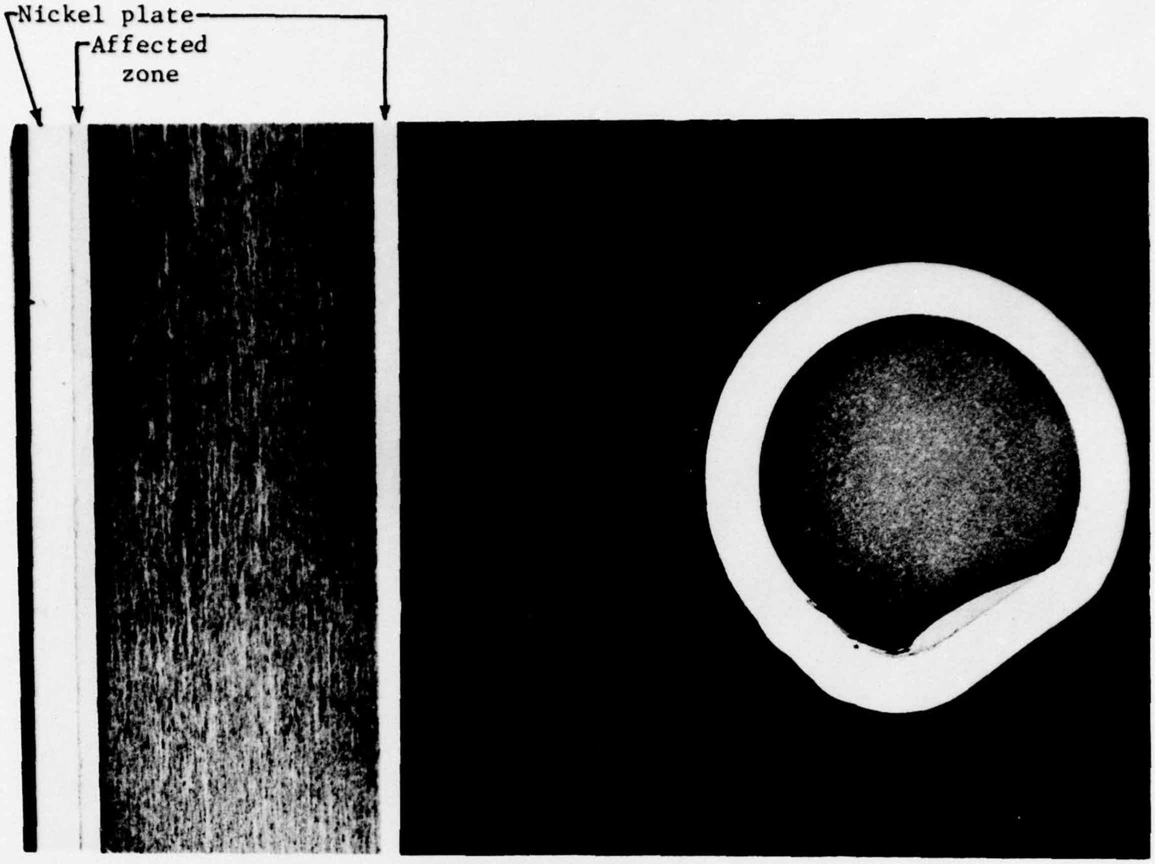
It was expected that frictional heating would occur in the wires during abrasion. However, the exact temperatures reached by the wires as a result of heat generated by the abrasion was not calculated.

Details of the metallographic examination follow.

The Extra-Improved Plow Steel Wire. Figure 9 shows photomicrographs of an abraded EIPS wire that had been nickel plated*, metallographically polished, and etched to reveal the microstructure. Figure 9a, at 20X magnification, clearly shows the affected zone in both the transverse and longitudinal wire sections. Examination at 750X magnification revealed that the unaffected region of the EIPS wire had a highly cold-worked structure that consisted of approximately 99 percent fine pearlite colonies and some fine, largely unresolved carbide particles as shown in Figure 9c. The affected structure was a white-etching material. From previous work of Battelle researchers, the white-etching material was thought to be a fine, untempered martensite.

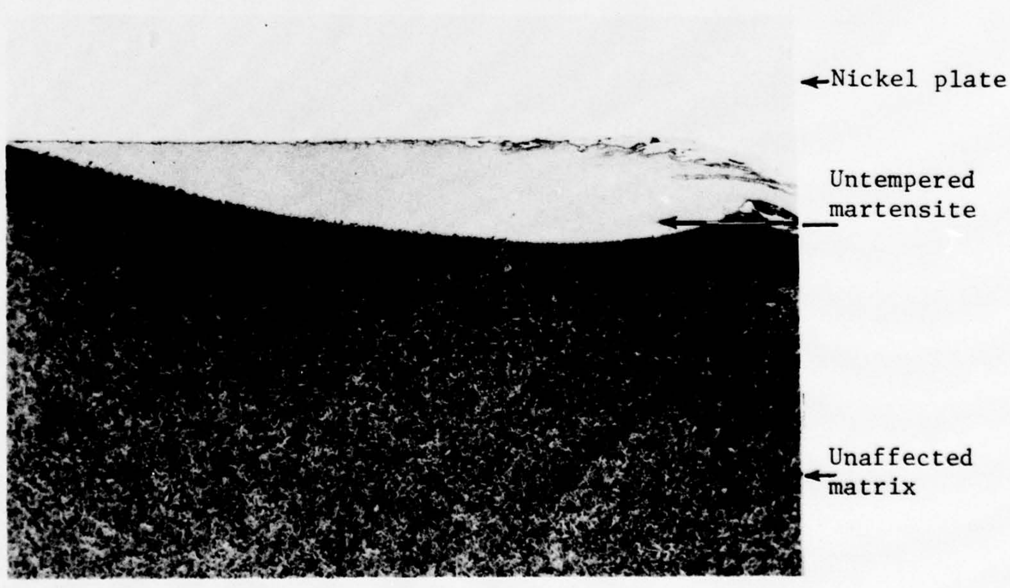
A simple experiment was performed to determine the nature of the white-etching layer. A small sample of abraded EIPS wire (taken from the same wire shown in Figure 9) was tempered for 1 hour at 600 F. The wire was then metallographically prepared and etched. The result of this experiment can be seen in Figure 10. The material that previously was white after etching now was dark after etching and revealed a structure. Upon examination at high magnification, the tempered structure was resolved and was determined to be entirely fine, tempered martensite. That result proved that the abrasion heated the

* The specimens were electroplated with nickel to provide mechanical support to the edges and minimize rounding during metallographic preparation.



20X Picral Etch

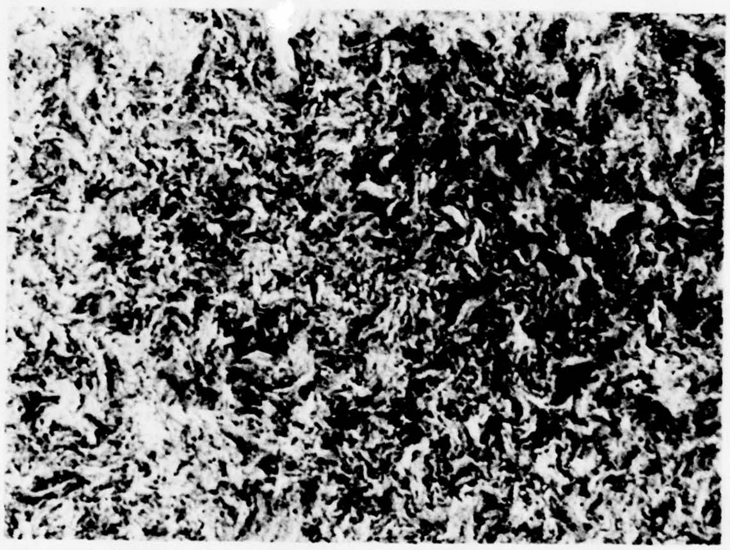
a. Longitudinal and Transverse Sections of the Abraded Wire



100X Picral Etch 7J504

b. The Affected Zone Caused by Abrasion, Shown at Higher Magnification; Transverse Section

FIGURE 9. THE STRUCTURE OF THE CONTROL ALLOY, EXTRA-IMPROVED PLOW STEEL (EIPS), AFTER ABRASION



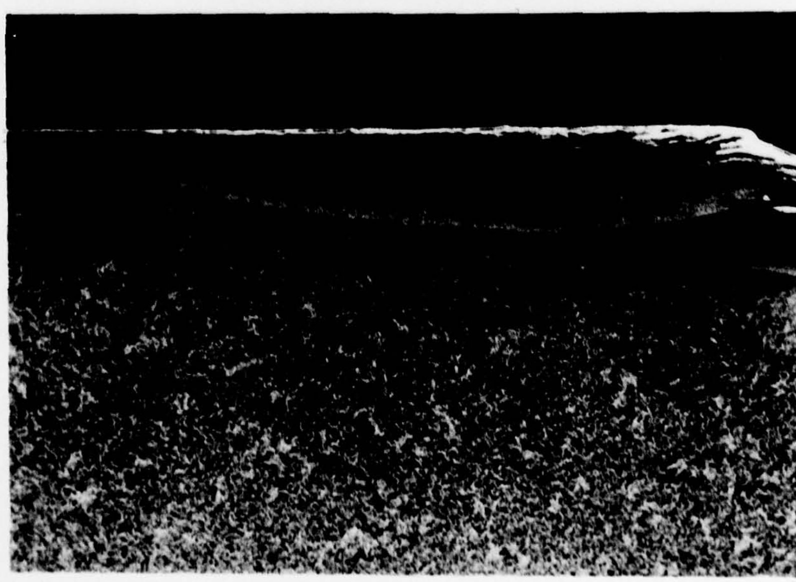
750X Picral Etch 7J507

FIGURE 9c. A HIGH MAGNIFICATION PHOTOMICROGRAPH SHOWING THE FINE PEARLITE AND CARBIDES PRESENT IN THE MATERIAL

The photograph was taken from the direction transverse to the longitudinal axis of the wire.

20X Picral Etch 7J505

a. Transverse and Longitudinal Wire Sections After Tempering



100X Picral Etch 7J506

b. The Tempered-Martensite Zone in the Transverse Section at Higher Magnification

FIGURE 10. THE ABRADED EIPS WIRE AFTER TEMPERING

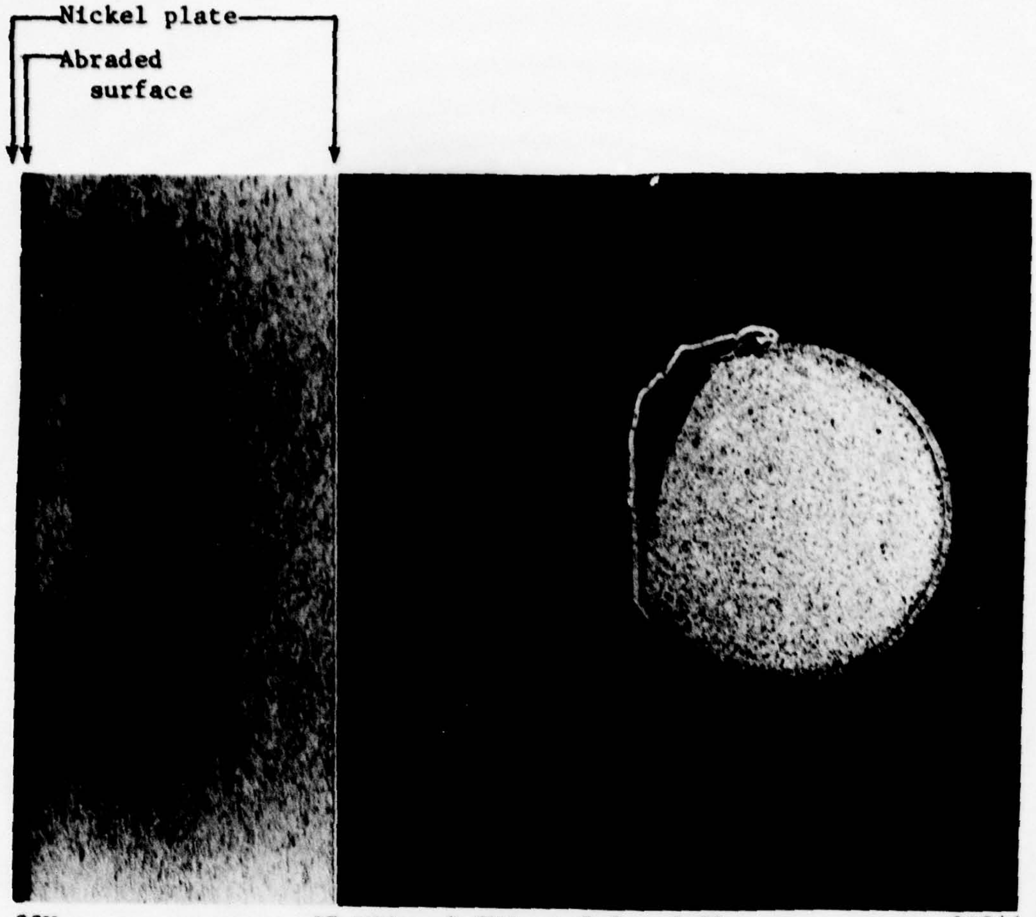
EIPS wire to a temperature above the upper critical, or above at least 1350 F, so that the surface layer consisted predominantly of austenite (although some fine carbide particles remained undissolved). The affected zone was immediately quenched by the surrounding mass of cold wire to form a hard and brittle untempered-martensite structure. This conslusion is substantiated by the hardness data for the affected zone of the EIPS wire before and after tempering, shown in Table 4. A Rockwell C hardness of 67 is the maximum theoretical hardness possible for untempered martensite in steels, and only untempered martensite could produce such a hardness in a quenched, fully austenitized AISI 1080 plain carbon steel. Therefore, it was concluded that the EIPS wire was austenitized in the affected zone by the heat generated by the abrasion, and upon cooling, was transformed to untempered martensite. The presence of untempered martensite is undesirable and could be catastrophic, causing a deck pendant to fail prematurely in service.

TABLE 5. HARDNESS MEASUREMENTS TAKEN FROM UNTEMPERED AND TEMPERED ABRADED EIPS WIRE SPECIMENS

Martensitic Structure	Response to Etchant	Knoop Hardness Value	Rockwell C Hardness (by Conversion)
Untempered	white	895	67
Tempered	dark; structure shown	733	60

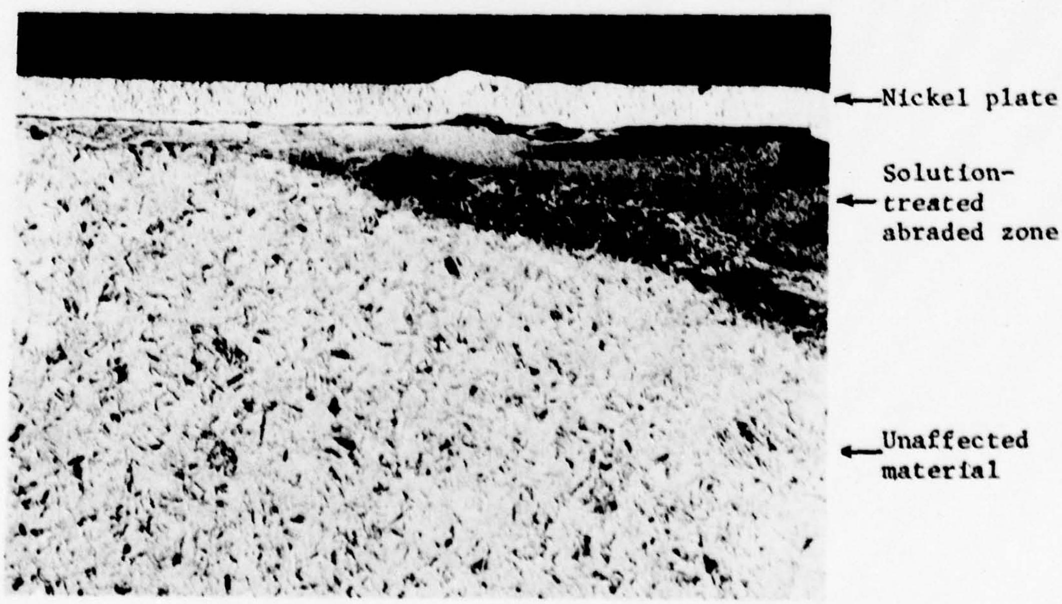
<u>Candidate Alloys</u>. Aside from the control wire material (EIPS), no other candidate alloy formed a hard, brittle structure or phase in the abrasion-affected zone.

In Figures 11, 12, and 13, the abraded regions are shown for the UCAR 302, Type 302 Special Process, and 11R51SH stainless steels, respectively. Extensive deformation and smearing of the wire materials occurred for all of these alloys, thereby reducing the effective cross-section of the wire. The unaffected structures seen in the figures are typical and contain highly cold-worked austenite, strain-induced martensite, and carbide particles.



20X 97 HCl - 3 HNO_3 + 0.5 g $CuCl_2$ 8J244

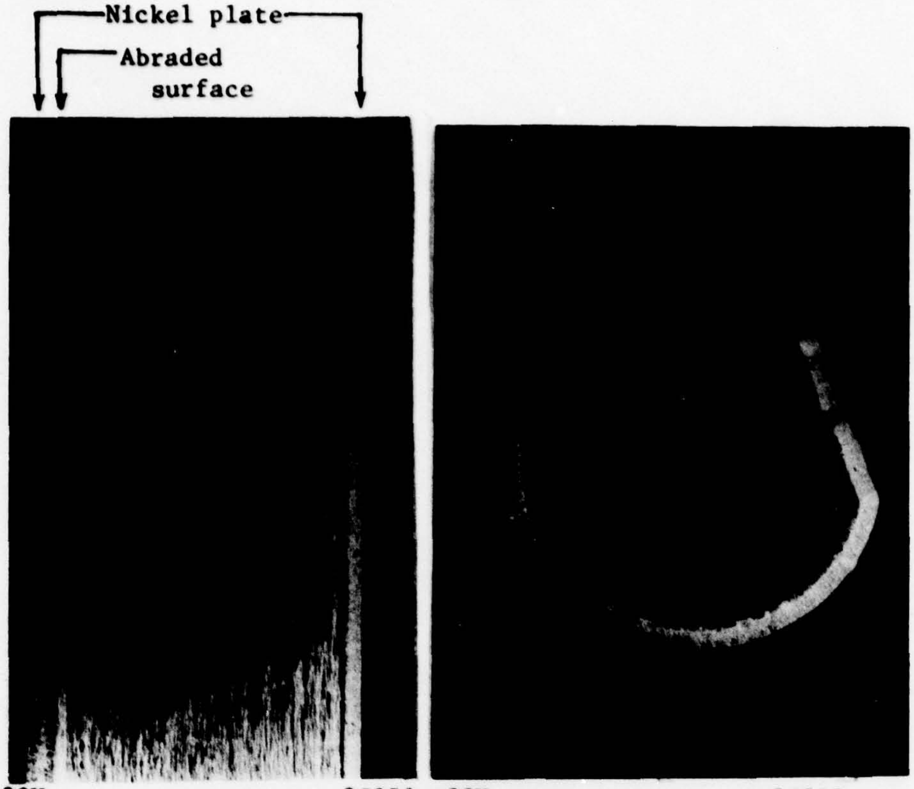
a. Longitudinal and Transverse Cross Sections of the Abraded Wire



100X 97 HCl - 3 HNO_3 + 0.5 g $CuCl_2$ 8J241

b. The Affected Zone in the Transverse Section, Shown at Higher Magnification

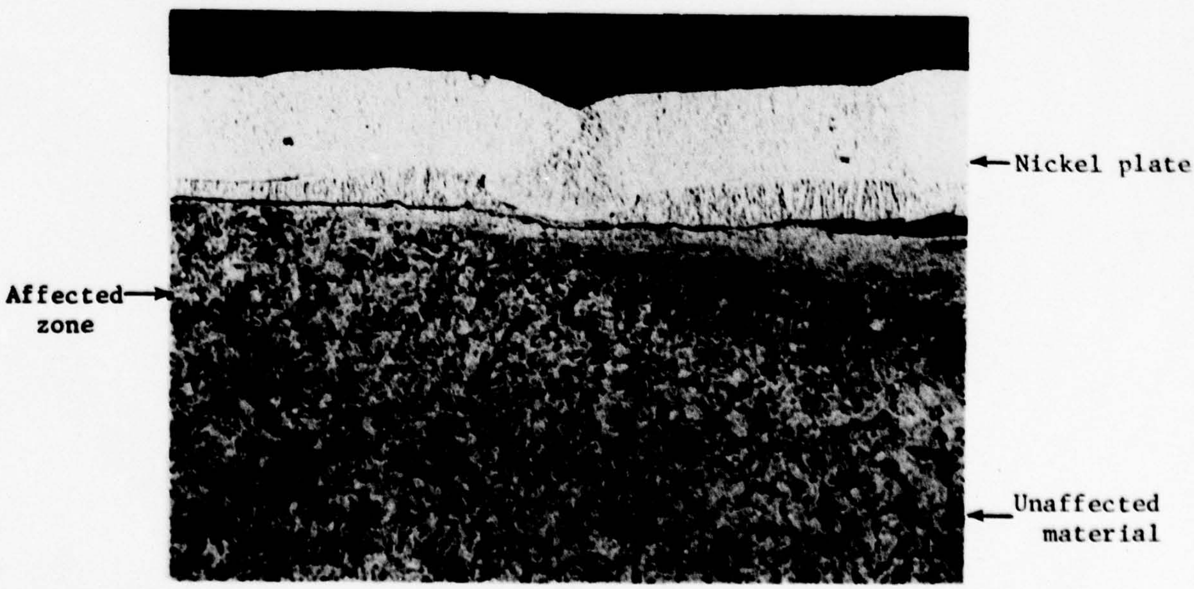
FIGURE 11. THE ABRADED UCAR 302-ALLOY WIRE



20X 8J250 20X 8J249

97 HCl - 3 HNO_3 + 0.5g $CuCl_2$

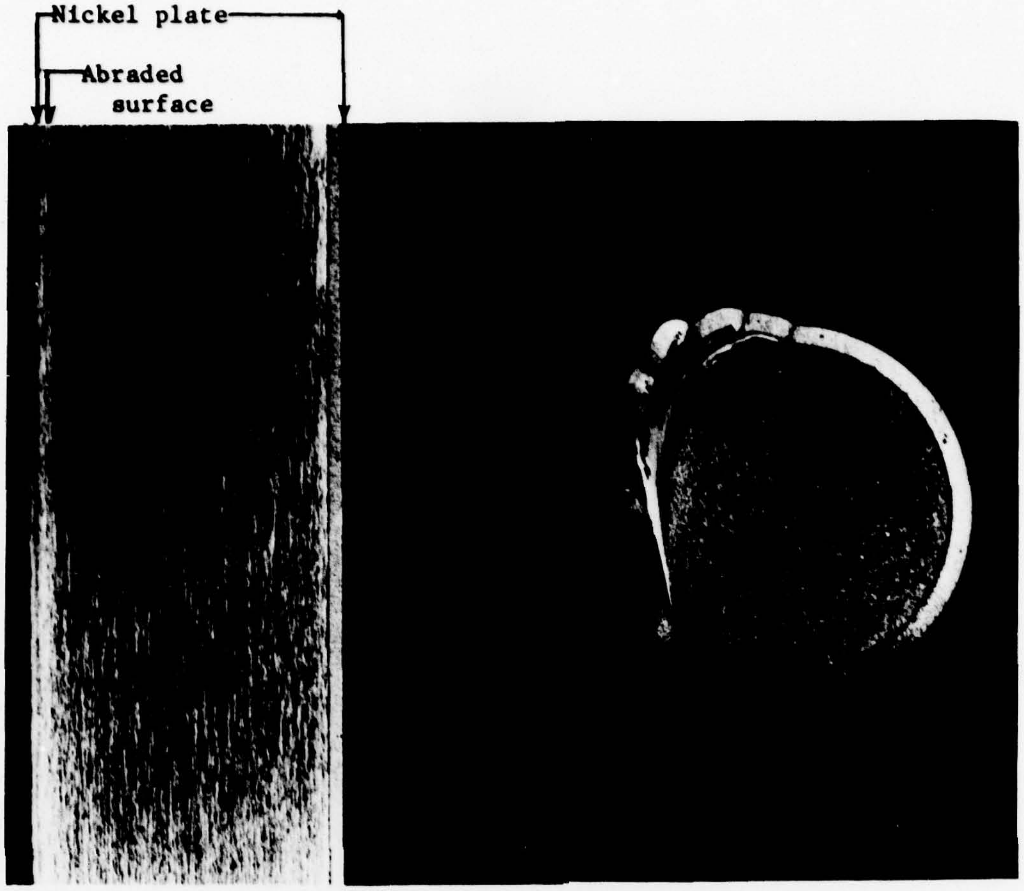
a. **Longitudinal** and Transverse Sections of the Abraded Wire. The Amount of **Material** Smeared From Abrasion is Exagerated by the Nickel Plate on the **Transverse** Cross-Section.



10X 97 HCl - 3 HNO_3 + 0.5 $CuCl_2$ 8J245

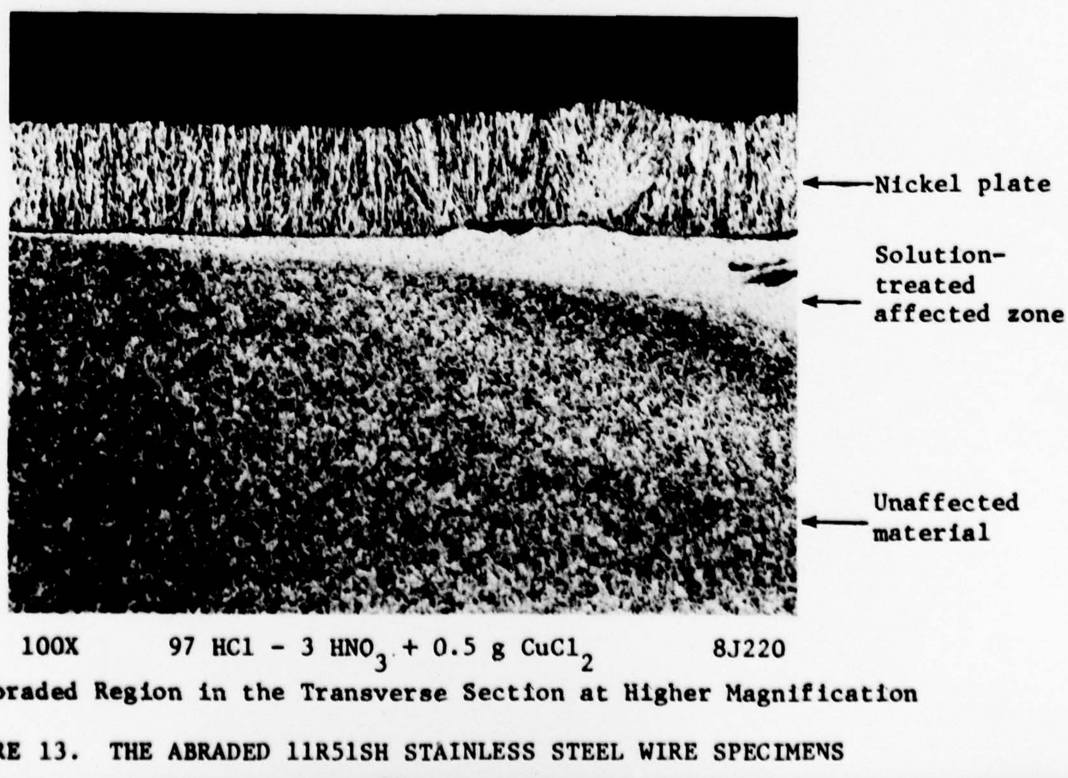
b. **Abraded Region in** Transverse Section at Higher Magnification. Note the **Change in Structure** in the Abraded Zone.

FIGURE 12. ABRADED TYPE 302 SPECIAL PROCESS ALLOY WIRE



20X 97 HCl - 3 HNO_3 + 0.5 g $CuCl_2$ 8J223

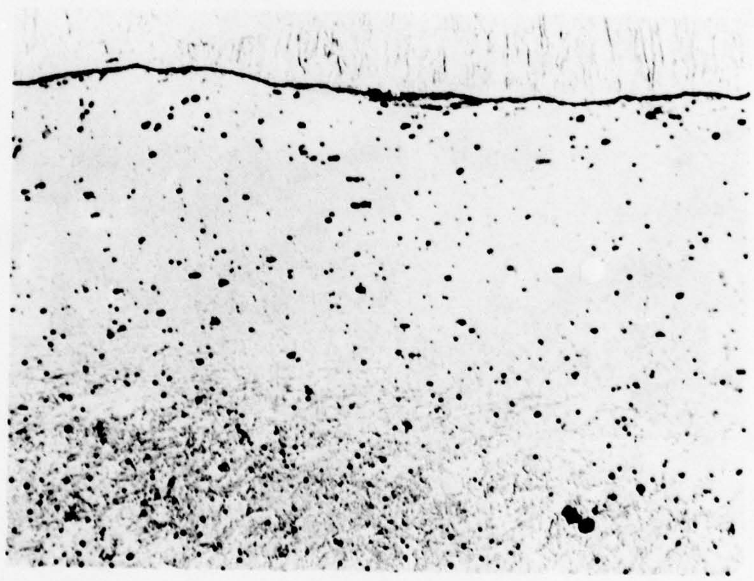
a. Transverse and Longitudinal Cross Sections of the Abraded Wire



100X 97 HCl - 3 HNO_3 + 0.5 g $CuCl_2$ 8J220

b. The Abraded Region in the Transverse Section at Higher Magnification

FIGURE 13. THE ABRADED 11R51SH STAINLESS STEEL WIRE SPECIMENS



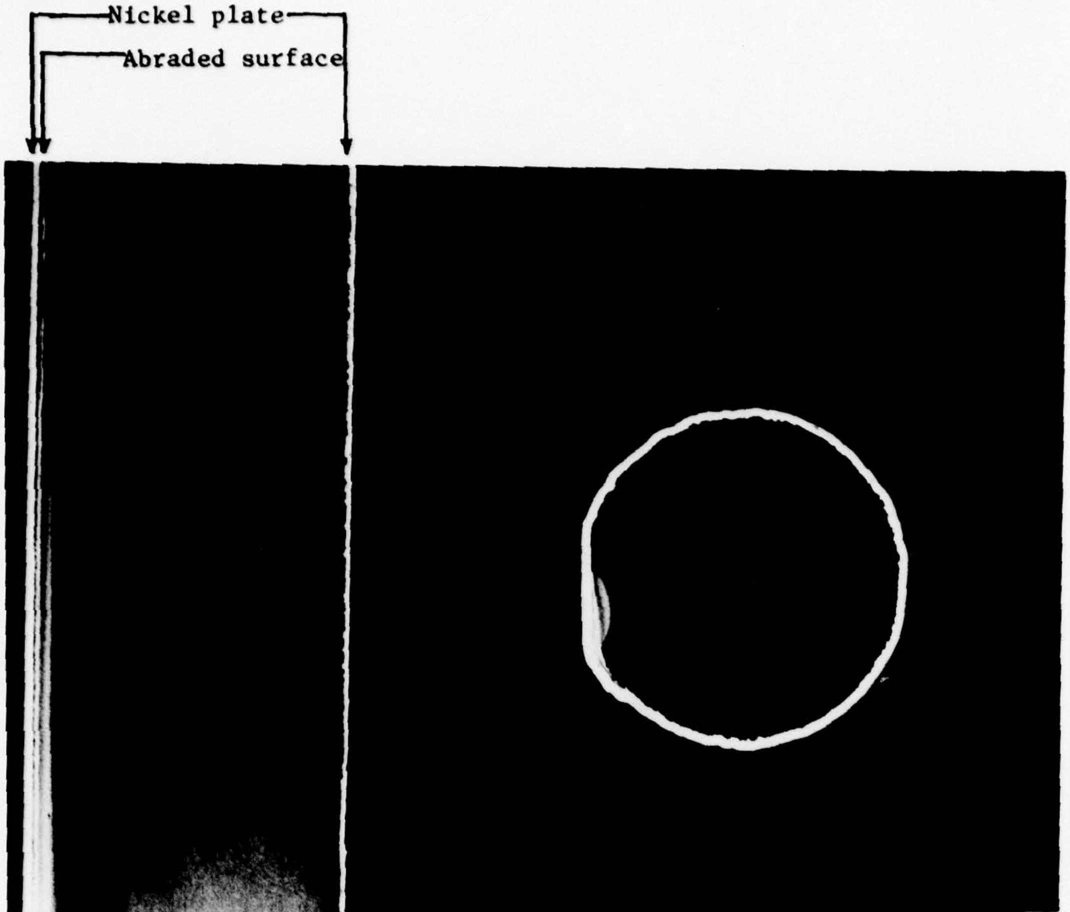
500X 8J222

97 HCl - 3 HNO_3 + 0.5g $CuCl_2$

c. High-Magnification Photomicrograph of the Solution-Treated Abraded Region

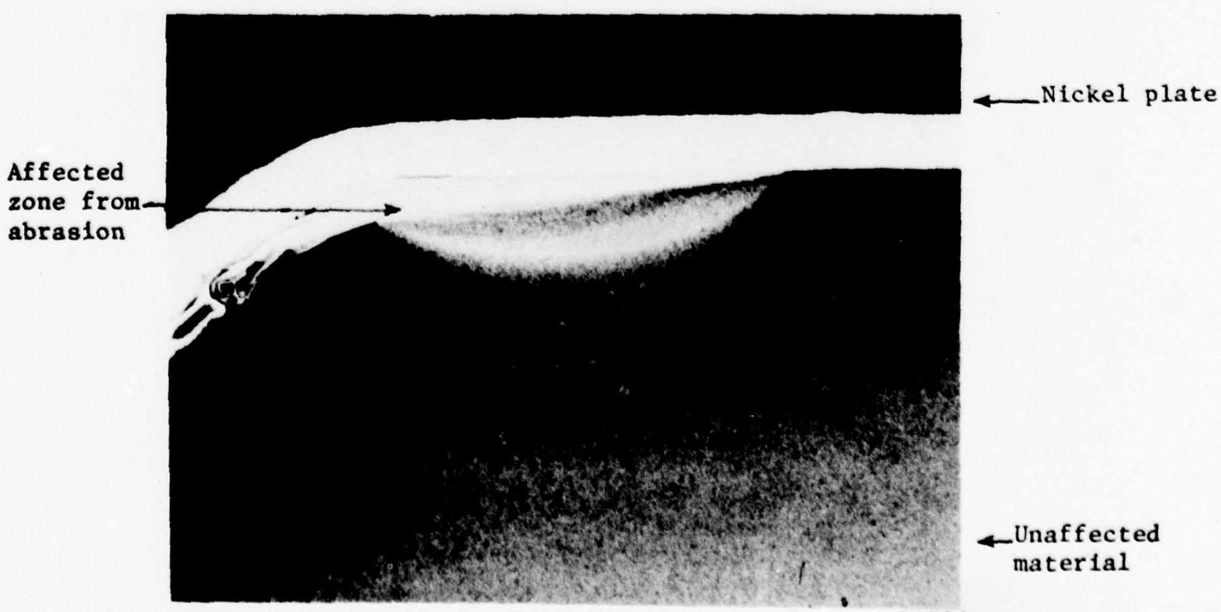
In the affected zones, the material appears to have been heated sufficiently high to solution treat the material. Thus, much of the former martensite and austenite in the affected regions was recrystallized to fine, strain-free austenite grains. The carbides were taken into solution upon heating, and then started to reprecipitate before quenching occurred. The exact nature of the abrasion-affected zones in these stainless alloys and, also, in the remaining materials, could not be identified exactly because of unknown effects introduced into the material with such a rapid heating and cooling cycle. With such cycles, the materials cannot react the same on an atomic basis as they do when solution treated for a longer time and then quenched. For example, the brief period of heating may not permit carbide particles to be dissolved completely, and the carbon content of the austenite may not be homogeneous. As is shown in Table 4, the affected zones in the stainless steels were softer than was the unaffected matrix material, thereby rendering those areas much less harmful than if a hard, brittle structure had been formed. In fact, surface softening may even be helpful in that it allows localized yielding in areas of high surface stress.

Figure 14 shows photomicrographs of the ALMAR 18 (300) Maraging steel in its abraded region. The unaffected structure was a fine, tempered martensite, which gives this steel its high strength. The abraded region consisted of a white layer of smeared material beneath the nickel plating, with a thumbnail-like zone beneath that. This thumbnail-shape zone was not fully explainable from the microstructure alone, but it was felt that the area was a result of some type of thermal effect whereby the material retained a greater amount of heat in that region longer than did the surrounding material. Thus, the thin, white, thumbnail-shape region of material was austenitized and quenched just as was the abraded material immediately adjacent to the nickel plate. Upon cooling, a tough, ductile, low-carbon, untempered martensite phase was formed. This martensite was considerably softer than was the matrix, because there was no aging treatment that would allow precipatation to occur. Notice that less material was smeared by the abrasion on this wire than was present on the ones discussed previously.



20X Picral Etch 8J227

a. Longitudinal and Transverse Sections of the Abraded ALMAR 18 (300) Wire



100X Picral Etch 8J224

b. A Higher Magnification View of the Abraded Region and White Band of Untempered Martensite

FIGURE 14. THE ABRADED ALMAR 18 (300) MARAGING-STEEL WIRE

In Figure 15, photomicrographs of the Elgiloy wire are seen. The typical unaffected structure was that of the strain-hardened, face-centered-cubic, solid-solution primary phase, with some modified hexagonal-close-packed structure that resulted from the aging process.

The affected zone was one of the shallowest in the seven candidate (and one control) alloys. The abraded region was heated, but not enough to fully change the microstructure. The abraded region, as seen in Figure 15, was plastically deformed and smeared. Partial solution treatment was experienced by the alloy. Obviously, this material was quite abrasion resistant, as were the next two alloys to be described.

Figure 16 shows photomicrographs of an abraded Inconel 718 wire. The typical microstructure of the material unaffected by abrasion was highly cold-worked δ-phase (solid solution) and δ'-phase (Ni_3 Al, Ti). The aging process precipitated Ni_3Nb along the grain boundaries and slip lines, as may be seen in the photomicrographs. The abrasion-affected material appeared to have been partially solution treated, with most of the Ni_3Nb precipitates having been dissolved. However, the affected region was so small (the smallest of any of the wires) that its effect on the material's mechanical properties was negligible.

Figure 17 shows photomicrographs of a transverse section from an abraded MP35N wire. The microstructure typical of this alloy in the regions unaffected by the abrasion was a face-centered-cubic, solid-solution, primary phase with a significant amount of a transformed hexagonal structure formed from the cold work during wire drawing. The hexagonal structure cannot be seen with a light microscope.

The abrasion-affected zone shows a partially solution-treated material having a very fine structure. Apparently, the very small affected zone had been heated to a high temperature, but the temperature did not significantly degrade the mechanical properties of the wire.

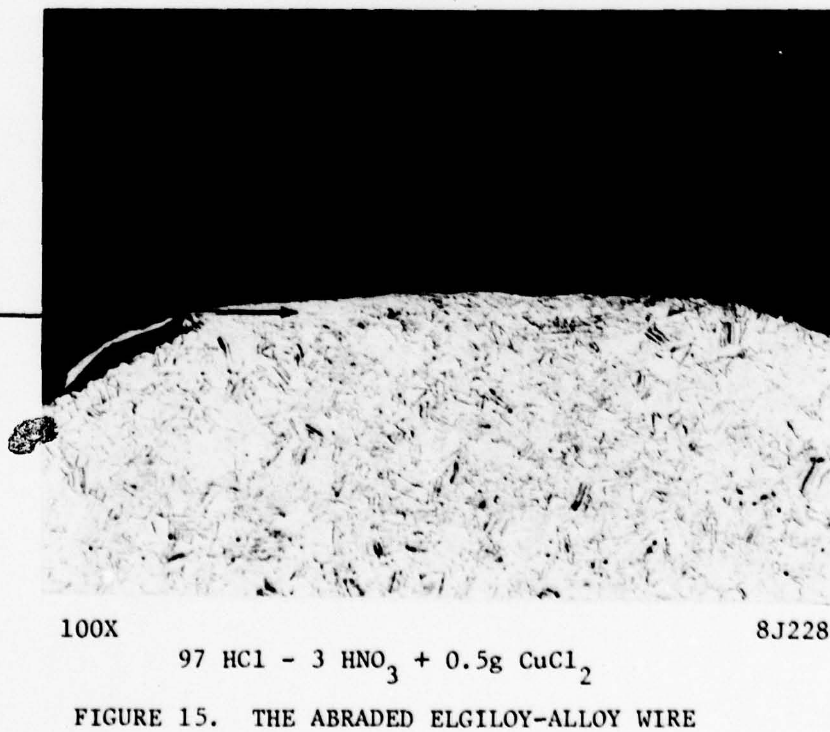
Affected zone

20X 8J232

97 HCl - 3 HNO_3 + 0.5g $CuCl_2$

a. **A Low-Magnification** View of the Transverse Section of the Abraded Wire

Plastically deformed, abraded region



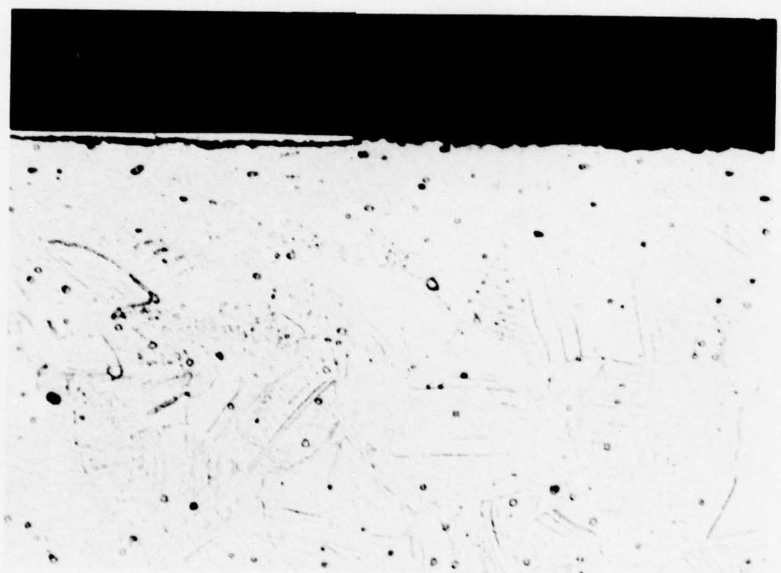
Unaffected matrix

100X 8J228

97 HCl - 3 HNO_3 + 0.5g $CuCl_2$

FIGURE 15. THE ABRADED ELGILOY-ALLOY WIRE

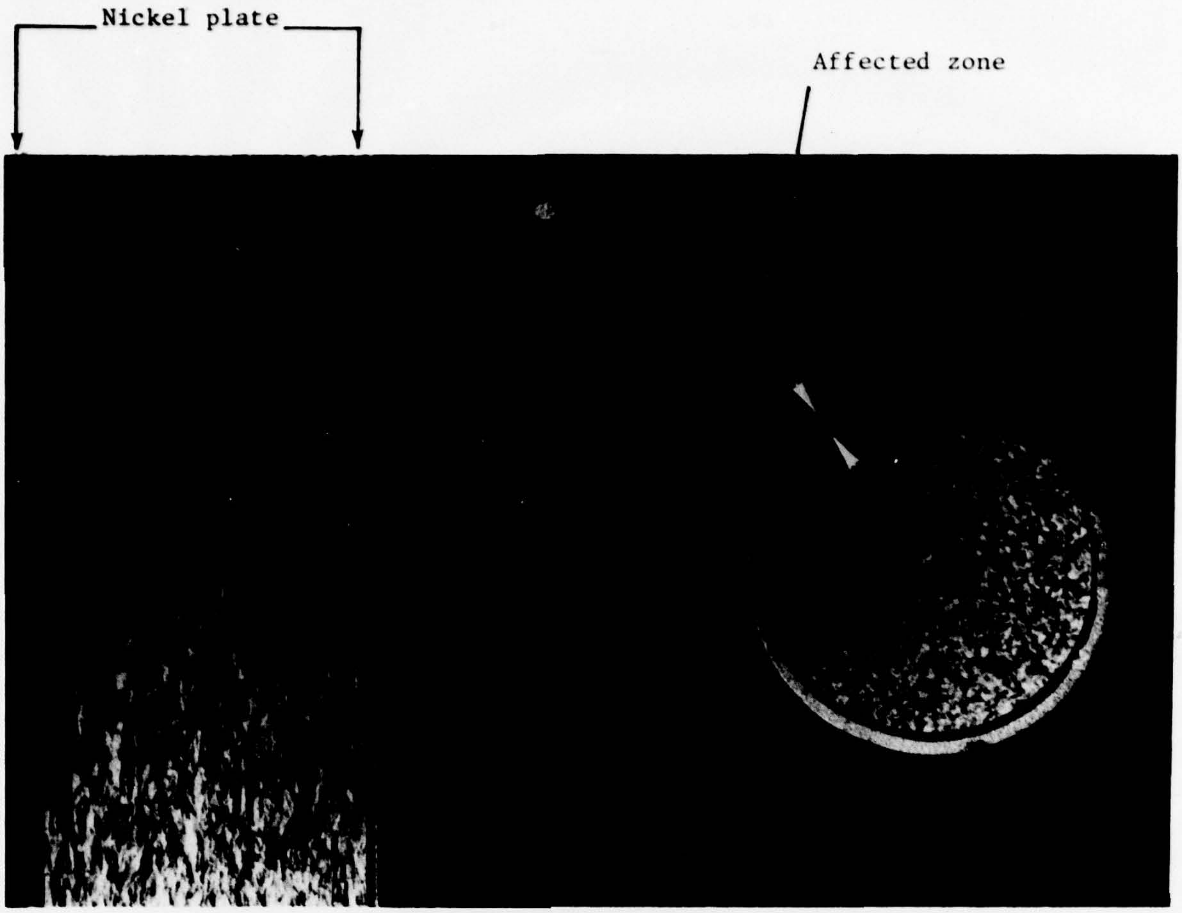
This wire was not nickel plated.



750X 8J231

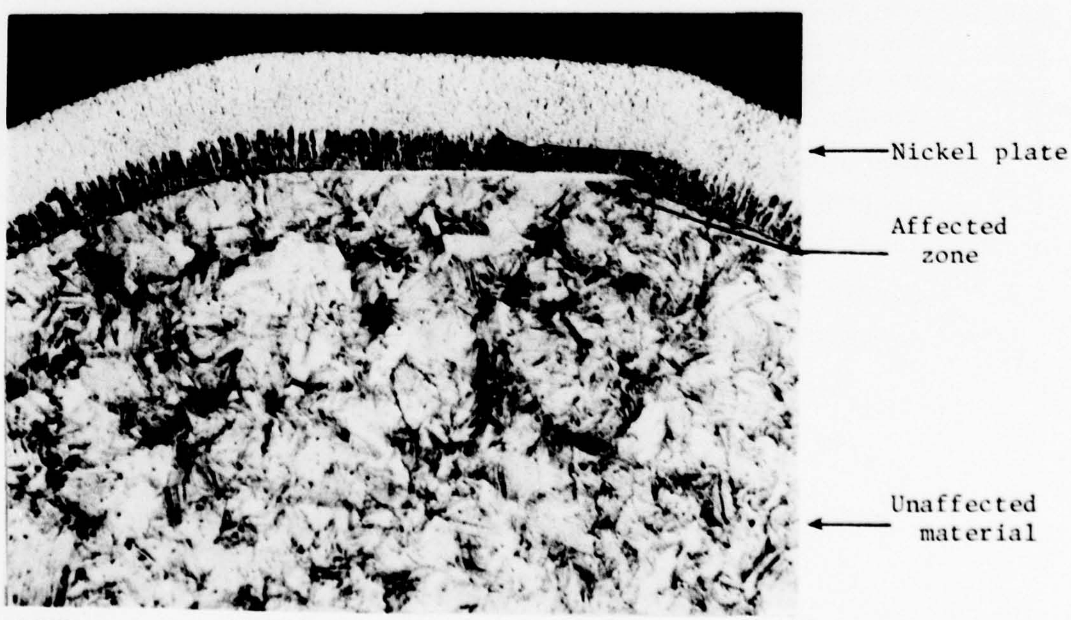
97 HCl - 3 HNO_3 + 0.5 g $CuCl_2$

FIGURE 15c. The Partially Solution-Treated Abraded Zone of the Wire



20X $97\ HCl - 3\ HNO_3 + 0.5g\ CuCl_2$ 8J236

a. Longitudinal and Transverse Sections of the Abraded Wire Show the Interesting Precipitate-Outlined, Cold-Worked Structure



100X $97\ HCl - 3\ HNO_3 + 0.5g\ CuCl_2$ 8J233

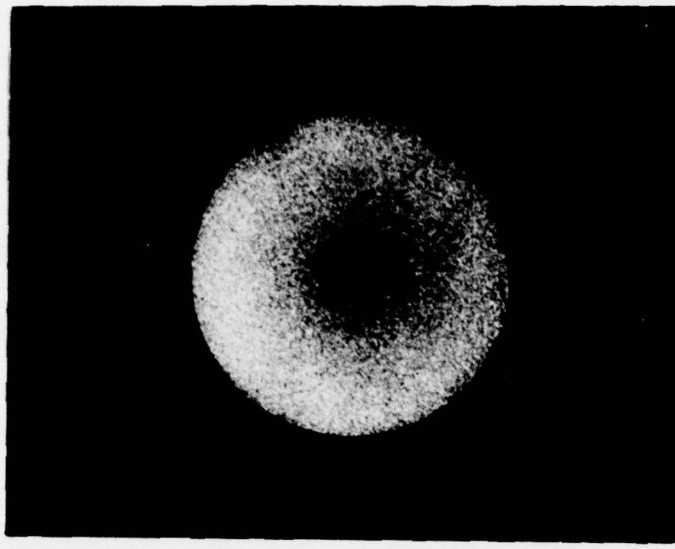
b. Note the Small Affected Zone

FIGURE 16. THE ABRADED INCONEL 718 WIRE

750X 8J235

$97\ HCl - 3\ HNO_3 + 0.5g\ CuCl_2$

FIGURE 16c. THE PARTIALLY SOLUTION-TREATED ABRADED ZONE
(Some precipitates can still be seen in the abraded region.)



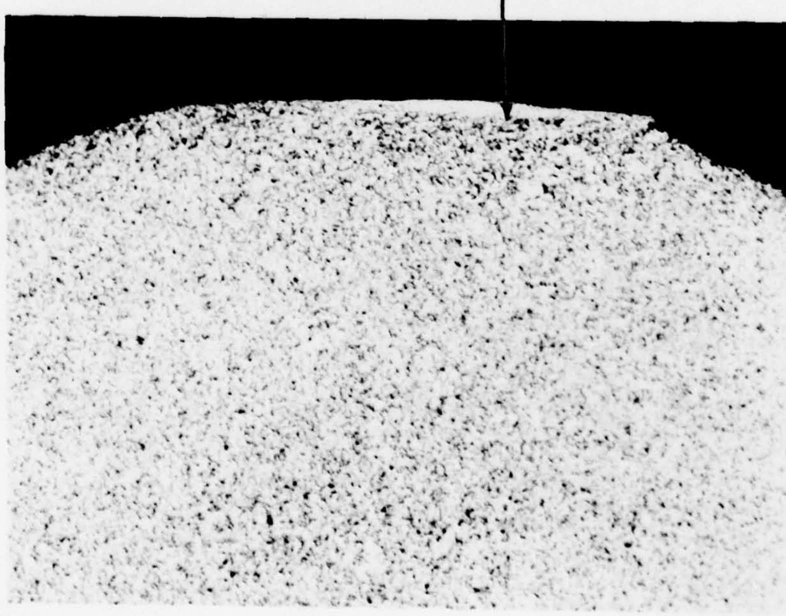
Abraded region

20X 8J240

97 HCl - 3 HNO_3 + 0.5g $CuCl_2$

a. Transverse Section of the Abraded Wire

Abraded area



Unaffected material

100X 8J237

97 HCl - 3 HNO_3 + 0.5g $CuCl_2$

b. The Small, Partially Solution-Treated Abraded Zone, Shown at Higher **Magnification**

FIGURE 17. THE ABRADED MP35N-ALLOY WIRE

This wire was not electroplated with nickel.

750X 8J239

97 HCl - 3 HNO_3 + 0.5g $CuCl_2$

FIGURE 17c. The Abraded Zone at High Magnification.

Task 5 - Mechanical Evaluation of Abraded Wires

The mechanical evaluation of wire specimens subjected to simulated - service abrasion tests provided information that characterized the response of single wires damaged by abrasion. Following abrasion, the wires were subjected to tension, torsion, and fatigue under bending and tension which simulated some of the stress states that may be experienced by the wires in deck-pendant wire rope during their service subsequent to the initial damage incurred from aircraft hook engagement. The purpose of the tests was to characterize the effect of abrasion on the mechanical properties of the wire. The experimental equipment and test procedures are discussed in the following section, together with the results.

Tension and Torsion Evaluation of Abraded Wires

Procedure. Tensile tests were performed on abraded-wire specimens having a 7-inch gage length (which was part of the 10-inch wire length between the tensile-tester grips). Three samples of each alloy were tested to failure. The torsion tests were performed on two abraded-wire samples of each alloy. These latter tests were similar to the torsion tests for unabraded wire; they ended with failure of the specimens. In addition, selected abraded wires that had been mechanically tested were examined under the stereomicroscope to characterize their fracture types and fracture surfaces.

Results. The results of the tensile and torsion tests are shown in Table 6. The alloys are listed in the same order as they appear in Table 2 (Task 2). The majority of the tensile failures occurred within the abraded zones on the wires, as would be expected. Specifically, the failures occurred near one end of the abraded zone.

The table shows that apparently more than half of the wire specimens had slightly increased tensile properties relative to the tensile-property values obtained for unabraded wires. The increases were so small (the largest being of the order of 3 percent) that it was felt that the abrasion had little effect

on the tensile properties and that the value differences for those materials were within the range expected for the equipment and the technique used to measure the cross-sectional area of the wires.

Nearly all of the torsion-test failures occurred in the abraded regions of the wires also. It should be noted that significant reductions did occur in the number of turns to failure for all specimens as the result of damage by abrasion. The values for the turns to failure for the abraded wires, as compared with the turns to failure for the corresponding unabraded wires, were reduced by 35 to 89 percent. Thus, abrasion had a negative effect on the response of the wires to surface torsional stresses and strains, as expected.

The fracture surfaces that were studied at low magnifications under a stereomicroscope appeared similar to the fractures for the unabraded specimens that had been tested similarly.

Single-Wire Fatigue Evaluation of Unabraded and Abraded Wires

Procedure. The single-wire fatigue machine, shown in Figure 17, applies to a wire specimen, a rapidly fluctuating, controlled tensile load that simulates the tensile-load variations seen during an aircraft arrestment. Simultaneously, the wire sample is subjected to bending and interstrand contact forces. Various combinations of tension, bending, and contact stresses can be programmed to achieve the desired combination and interaction of stress conditions.

For the notch-fatigue experiments conducted on candidate deck-pendant-wire alloys, a constant-amplitude cyclic tension and cyclic cross-wire contact force were applied in phase. A load cell was mounted in series with the test specimen to continuously monitor actual load patterns. To begin each experiment, the maximum tension was adjusted to 1075 pounds and the corresponding maximum contact force was set at 600 pounds. This combination of loading resulted in a minimum cyclic load of about 275 pounds. A segment of a typical tensile-load history for one of the wires is shown in Figure 18. For a 0.090-inch-diameter wire, this load pattern resulted in a maximum stress of about

TABLE 6. MECHANICAL PROPERTIES, AFTER ABRASION, OF THE COMMERCIAL ALLOY WIRE CANDIDATES THAT WERE ACCEPTED FOR FURTHER STUDY

Alloy	Wire-Material Number	Heat Treatment	Reduction in Area, percent	Elongation, percent in 10 inches	Yield Strength[a], psi	Ultimate Tensile Strength, psi	Number of Turns to Failure in Torsion
11R51SH	13	As drawn	42.9	0.9	291,800	340,200	3.0
UCAR 302[b]	7	As drawn	49.6	0.5	314,600	317,000	1.3
ALMAR 18 (300) Maraging steel	10	Aged	49.5	0.6	305,800	315,600	1.3
Elgiloy	11	Aged 900 F, 5 hr, air cooled	27.9	0.6	276,000	318,000	1.0
Inconel 718	12	Double age: 1325 F, 8 hr, air cooled; 1150 F, 8 hr, air cooled	6.6	0.7	283,900	302,700	1.7
Extra-improved plow steel	4	As drawn	19.8	0.8	260,600	282,300	13.3
MP35N	9	As drawn	50.1	2.4	237,700	289,300	2.0
Type 302 Special Process[c]	2	As drawn	45.3	0.8	255,300	277,600	2.0

(a) Yield strength at 0.2 percent offset.

(b) Cryogenically deformed Type 302.

(c) Manufactured using an undisclosed "special process" which does not involve cryogenic deformation.

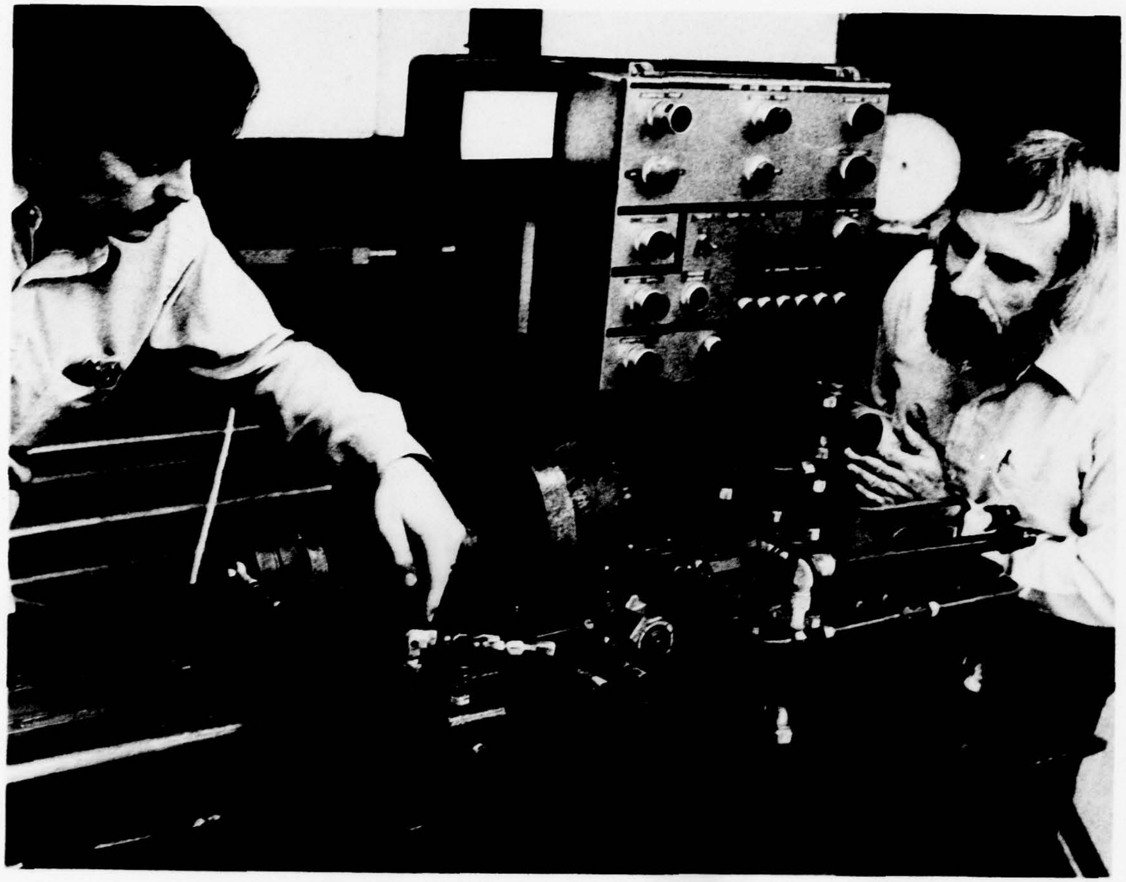


FIGURE 18. SINGLE-WIRE NOTCH-FATIGUE MACHINE

120,000 pounds/inch^2 and a cyclic stress range of about 90,000 pounds/inch^2. The cyclic frequency was about 0.9 cycle/second.

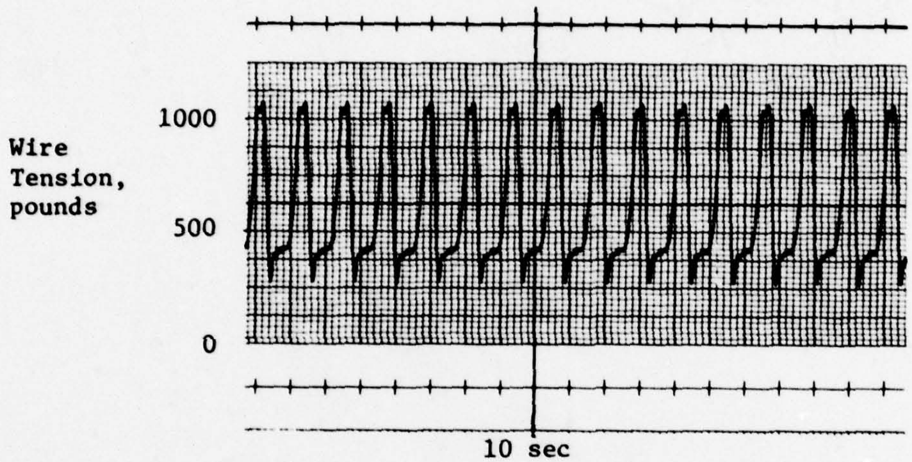


FIGURE 19. SEGMENT OF LOAD-TIME HISTORY FOR SPECIMEN EIPS-3 TESTED IN THE SINGLE-WIRE FATIGUE MACHINE

Results. Four* candidate wire alloys and the control wire alloy (extra-improved plow steel) were tested in the single-wire fatigue machine. Both abraded and unabraded wire samples were tested. Three wires of the extra-improved plow steel were tested for each condition, while two wires of each of the four candidate wire materials were tested for each condition. The resulting data are shown in Table 7.

Reduction in fatigue life due to abrasion ranged from over 80 percent for the extra-improved plow steel samples to only 40 percent for the MP35N samples. Alternatively, if the wires were ranked on the basis of abraded-wire fatigue resistance, Elgiloy would be the highest and 11R51SH the lowest.

* Three of the candidate wire materials listed in Table 5 were eliminated prior to these tests, thereby decreasing the total to four. The eliminated materials were Type 302 Special Process, UCAR 302, and ALMAR 18 (300) Marging Steel. The first two materials were eliminated because of their poor performance in the abrasion test, while the latter material was eliminated on the advice of the Naval Air Systems Command Technical Monitor.

TABLE 7. SINGLE-WIRE FATIGUE TEST RESULTS FOR FIVE CANDIDATE DECK-PENDANT-WIRE MATERIALS

Wire Material	Abraded Wires			Unabraded Wires			Percent Reduction in Failure Life Unabraded to Abraded
	Specimen Number		Bending & Tension Cycles to Failure	Specimen Number		Bending & Tension Cycles to Failure	
Extra-Improved Plow Steel	3A		5,650	6		19,382	
	4A		4,489	7		22,942	
	12A		2,630	8		23,435	
		Avg.	4,260		Avg.	21,920	81
11R51SH	4A		4,173	1		13,259	
	12A		3,138	2		16,734	
		Avg.	3,630		Avg.	15,000	75
Inconel 718	4A		5,589	1		8,778	
	12A		2,666	2		8,855	
		Avg.	4,130		Avg.	8,820	53
Elgiloy	4A		14,085	1		27,546	
	12A		9,950	2		23,045	
		Avg.	12,020		Avg.	25,300	52
MP35N	4A		7,138	1		13,543	
	12A		8,621	2		12,600	
		Avg.	7,880		Avg.	13,070	40

Task 6 - Recommendations of Promising Candidates for Rope Manufacture

A number of factors must be considered before a wire alloy can be recommended for experimental rope manufacture and evaluation for the deck-pendant application. From the various tests completed in this program, it is possible to assess directly or indirectly the promise of particular wire alloys for rope manufacture and deck-pendant service.

Ultimate tensile strength (UTS) was used as the first discriminator. Using tensile-test results for unabraded wires (reported in Table 2), it is possible to screen the initial list of 14 candidate wire alloys (plus the control material, extra-improved plow steel) and to eliminate 7 of the 15 on the basis of insufficient UTS. The criterion for rejection of most of the alloys was a UTS below about 285 ksi. One alloy having a UTS of about 284 ksi was also rejected for low reduction in area values. The other alloys rejected for low UTS displayed tensile strengths from 271 ksi for the Type 302 to 238 ksi for the 17-7 PH. These strength levels ranged from 6.5 to 21 percent below that for extra-improved plow steel. The wire alloys rejected on the basis of low UTS are noted in Table 8.

With 7 candidate wire materials remaining, the abrasion resistance of these alloys and their possible tendency to form a brittle transformation product at the abraded surface was compared against that of the control material. None of the 7 candidate alloys was found to form a brittle surface layer--although the EIPS control material was found to form untempered martensite. As noted earlier in Table 3, the resistance to abrasion of the candidate alloys varies substantially. The abrasion resistance of each alloy is summarized qualitatively in Table 9. It is possible to distinguish 3 distinct categories of abrasion resistance; these categories are noted as poor, average, and excellent. Both remaining types of Type 302 stainless steel wires displayed poor abrasion resistance and, therefore, were rejected from further study. The extra-improved plow steel, ALMAR 18 and 11R51SH displayed what was considered average abrasion resistance. However, although the abrasion performance of ALMAR 18 was good enough to be retained for further study, the NAVAIR Technical Monitor informed Battelle of his doubts concerning the ultimate serviceability of the ALMAR 18 alloy; therefore, it was rejeced. The three wire materials displaying excellent abrasion resistance (as well as 11R51SH) were retained for final evaluation.

TABLE 8. INITIAL DISCRIMINATOR FOR CANDIDATE WIRE MATERIALS: ULTIMATE TENSILE STRENGTH

Wire Material Number	Alloy	Retain	Reject	Reason for Rejection
1	NS 18-2		✓	UTS[a] of only 270
2	Type 302 Special Process	✓		
3	17-7PH		✓	UTS of only 238
4	Extra-Improved Plow Steel (EIPS)	✓		
5	Type 302 Stainless		✓	UTS of only 271
6	Type 304 Stainless		✓	UTS of only 261
7	UCAR 302	✓		
8	18-18 Plus		✓	UTS of 284 but RA[b] of only 2.9%
9	MP35N	✓		
10	ALMAR 18	✓		
11	Elgiloy	✓		
12	Inconel 718	✓		
13	11R51SH	✓		
14	Pyromet 31		✓	UTS of only 258
15	Type 316 HSM		✓	UTS of only 241

(a) UTS — Ultimate tensile strength, ksi; UTS for EIPS is 288 ksi.

(b) RA — Reduction in area; RA for EIPS is 45.7 percent.

TABLE 9. SECONDARY DISCRIMINATOR FOR CANDIDATE WIRE MATERIALS: RESISTANCE TO ABRASION

Wire Material Number	Alloy	Brittle Surface Layer Formed by Abrasion?	Abrasion Resistance	Effect of Abrasion on Mechanical Properties		Retain	Reject	Reason for Rejection
				Tension	Torsion			
2	Type 302 Special Process	No	Poor	Small	Large		✓	Poor abrasion resistance
4	Extra-Improved Plow Steel (EIPS)	Yes	Average	Small	Moderate	✓		
7	UCAR 302	No	Poor	Small	Small		✓	Poor abrasion resistance
9	MP35N	No	Excellent	Small	Moderate	✓		
10	ALMAR 18	No	Average	Small	Small		✓	Average abrasion resistance; however, rejected at the NAVAIR Monitor's suggestion
11	Elgiloy	No	Excellent	Small	Small	✓		
12	Inconel 718	No	Excellent	Small	Moderate	✓		
13	11R51SH	No	Average	Small	Moderate	✓		

TABLE 10. TERTIARY DISCRIMINATOR FOR CANDIDATE WIRE MATERIALS: EFFECT OF ABRASION ON FATIGUE PERFORMANCE

Wire Material Number	Alloy	Basic Strength Characteristics, Unabraded Wire		Effect of Abrasion on Fatigue Performance		Material Cost, $/lb, June, 1979*
		UTS, ksi	TYS, ksi	Abraded Life, cycles x 10^3	Reduction in Life, percent	
4	Extra-Improved Plow Steel (EIPS)	288	238	4.3	81	0.44
9	MP35N	286	224	7.9	40	50.00
11	Elgiloy	313	277	12.0	52	44.79
12	Inconel 718	293	283	4.1	53	10.89
13	11R51SH	340	288	3.7	75	3.10

Note: UTS - Ultimate tensile strength, ksi; TYS - Tensile yield strength, ksi.

* Based on 3000-lb quantities. Prices do not include heat treatment.

With 4 of the original 14 candidate wire materials and the control material remaining, single-wire fatigue tests were performed as a final discriminator. These data are reported in Table 7.

Using all the data available, it is possible to construct a table of important mechanical properties and cost information and to break these data into four categories related directly or indirectly to strength, manufacturability, effect of abrasion on fatigue performance, and cost. This information is shown in Table 10 for the 4 more promising candidate wire alloys along with that for the control material. Ultimate tensile strength (UTS) and tensile-yield strength (TYS) properties are obviously directly related to strength. High values for reduction in area, torsions-to-failure and the breadth of separation between the UTS and the TYS can be considered indicators of good manufacturability. The single-wire fatigue life of abraded wires (both in actual cycles and in percent reduction in life as a result of single-wire abrasion) was considered a good indicator of resistance to abrasion damage. In addition, none of the candidate materials was found to undergo a damaging transformation as a result of abrasion. Finally, material cost provided a direct indicator of relative rope costs.

Considering the many factors that can be used to rank the candidate alloys, how does one select the one or two superior alloys for future rope manufacture? First of all, it seems reasonable to consider that all four candidate wire alloys will have adequate strength; therefore, this parameter is not critical. Second, in view of the critical application in mind, it seems likely that a significant increase in costs could be traded off for superior reliability and safety. However, the cost/reliability/life relationships for the candidate alloys remain obscure. The properties measured are only indicators of reliability and it was beyond the scope of this program to quantify cost/reliability relationships. In addition, since the program was initiated, the cost of most of the promising candidate alloy have soared. Not only are MP35N and Elgiloy the two most expensive of the candidate alloys, but the selling price of these alloys has increased very substantially within the last three years. As shown in Table 1, their selling prices are between 2.5 and 3.2 times as great in June, 1979, as they were in July, 1976. Much of this increase is due to the very great increase in the price of cobalt, and the

large increase in the price of molybdenum, during that same time period; both alloys contain significant amounts of these two elements. These elements, in addition to increasing in price, have become less available on the market. Therefore, although we have shown indications that significant improvements in reliability and life would be experienced should ropes of MP35N and Elgiloy be subjected to pendant service, their dramatically escalating cost would appear to make them too high priced for use as deck-pendant materials.

Alternatively, both 11R51SH and Inconel 718 appear to offer improved reliability relative to extra-improved plow steel because they exhibit no damaging transformations under abrasion conditions. However, it remains to be seen if a significant fatigue life advantage (over that characteristic of EIPS) can be demonstrated for ropes made from these alloys.

In conclusion, it is recommended that attempts be made to make experimental ropes from both 11R51SH and Inconel 718. The manufacturability of rope from Inconel 718 would appear to be difficult because of its low values for reduction-in-area and UTS-TYS but should it be able to be produced, its fatigue life unabraded and abraded should equal or better than that of EIPS. (Because of the relatively high cost of all of the candidate materials only the cover wires of the strands should be made from the high-cost material; the balance of the rope should be EIPS.)

Ropes made from 11R51SH would be expected to be relatively easy to manufacture and their unabraded fatigue lives should be satisfactory. However, it appears that their fatigue lives under multiple abrasion-impacts would be seriously degraded.

Neither of the above alloys would be expected to form a brittle transformation product on the wire surfaces of the deck pendant contact by the hook. Therefore, although the fatigue lives for 11R51SH and Inconel 718 would be expected to be of the same order of that for EIPS, their service life should be more predictable.

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